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Site suitability assessment for green hydrogen production in the Valencian Community (Spain)

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Site suitability assessment for green hydrogen production in the Valencian Community (Spain).

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Abstract

The Next Generation funds have promoted energy transition projects and specially in Spain many green hydrogen projects are being presented throughout the territory. When developing renewable hydrogen-related projects multiple parameters and inputs must be considered since the characteristics of the sites' surroundings will have a great impact in the profitability of the project.

The main objective of this master thesis is to develop a methodology which helps with the process of selecting a suitable site to deploy a green hydrogen production facility. The study is limited to the green hydrogen production through electrolysis in the Valencian Community. It starts with georeferenced data gathering of the identified parameters that may have an impact in the viability of the project such the sun, wind and water resources available as well as the transportation infrastructures and main hydrogen potential consumptions. Special attention is given to the water allocation since hydrogen could be exported and with it, the water resources from the Valencian Community. Afterwards this data is processed in a geographic information system software by performing a multi-criteria weighted overlay analysis. The weight of each criteria is given following the Analytic Hierarchy Process.

Once these steps have been completed, a suitability map of the Valencian Community is obtained in which one can see the most suitable locations to deploy green hydrogen production projects based on the selected criteria. In this thesis, the sites with the highest suitability score are selected in each of the three provinces of the Valencian Community and several parameters such as the green hydrogen production potential in tons/year or the levelized cost of hydrogen (LCOH) have been calculated.

The results showed many similarities among the three locations in terms of green hydrogen production and LCOH due to its relatively close geographical situation. However, interesting findings such as the crucial need of having nearby a source of available water and the key role of desalination plants have been depicted.

Keywords: Green hydrogen, renewable electricity, solar, wind, water, electrolysis, proton exchange membrane, desalination, levelized cost of hydrogen, Valencian Community.

Sammanfattning

Next Generation-fonderna har främjat energiomställningsprojekt och särskilt i Spanien presenteras många gröna vätgasprojekt över hela territoriet. Vid utveckling av förnybara vätgasrelaterade projekt måste flera parametrar och ingångar beaktas eftersom egenskaperna hos platsernas omgivning kommer att ha stor inverkan på projektets lönsamhet.

Huvudsyftet med denna masteruppsats är att utveckla en metod som hjälper till med processen att välja en lämplig plats för att driftsätta en produktionsanläggning för grön vätgas. Studien är begränsad till grön vätgasproduktion genom elektrolys i Valencia-regionen. Den börjar med georefererad datainsamling av de identifierade parametrarna som kan ha en inverkan på projektets genomförbarhet, såsom tillgängliga sol-, vind- och vattenresurser samt transportinfrastruktur och huvudsakliga potentiella vätgasförbrukningar. Särskild uppmärksamhet ägnas åt vattentilldelningen eftersom vätgas kan exporteras och därmed vattenresurserna från Valencia-regionen. Därefter bearbetas dessa data i ett geografiskt informationssystem genom att utföra en viktad överlagringsanalys med flera kriterier. Vikten av varje kriterium ges enligt den analytiska hierarkiprocessen.

När dessa steg har slutförts erhålls en lämplighetskarta över regionen Valencia där man kan se de lämpligaste platserna för att genomföra projekt för produktion av grön vätgas baserat på de valda kriterierna. I denna avhandling väljs de platser med högst lämplighetspoäng i var och en av de tre provinserna i Valencia-regionen och flera parametrar som den gröna vätgasproduktionspotentialen i ton/år eller den nivellerade kostnaden för vätgas (LCOH) har beräknats.

Resultaten visade många likheter mellan de tre platserna när det gäller produktion av grön vätgas och LCOH på grund av deras relativt nära geografiska läge. Det har dock gjorts intressanta upptäckter, t.ex. det avgörande behovet av att ha en tillgänglig vattenkälla i närheten och avsaltningsanläggningarnas nyckelroll.

Nyckelord: Grön vätgas, förnybar el, solenergi, vindkraft, vatten, elektrolys, protonbytesmembran, avsaltning, nivåkostnad för vätgas, Valencianska gemenskapen.

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Table of Contents

List of Tables

List of Figures

Nomenclature

Abbreviations

AHP	Analytic Hierarchy Process
BoP	Balance of Plant
Demi	Demineralized/Deionized
EDI	Electrodeionization
GHI	Global Horizontal Irradiation
GIS	Geographical Information System
HRS	Hydrogen Refuelling Station
IEA	International Energy Agency
MCDA	Multi-criteria Decision Analysis
MCWOA	Multi-criteria Weighted Overlay Analysis
PPA	Power Purchase Agreement
PV	Photovoltaic
UN SDGs	United Nations Sustainable Development Goals

Symbols

GW	Gigawatt
H_2	Hydrogen
H_2O	Water
kW	Kilowatt
kWh	Kilowatt-hour
MW	Megawatt

1 Introduction

On the 27th of April 2021, the Spanish Government published the "Plan de recuperación, transformación y resiliencia" (PRTR) which aimed to help with the recovery of the country from the COVID-19 crisis and support a structural transformation that will lead to sustainable development of Spain [1]. In this context, the Next Generation EU funds lead to the deployment of this plan. Specifically, in the PRTR there is a roadmap of renewable hydrogen whose goal is to make Spain the lead in the hydrogen development. Therefore, more than 1500 M€ will be invested in order to achieve several sustainability goals for 2030 in Spain such as 4GW of electrolysers or a vehicle sector with 5000 - 7000 hydrogen combustion vehicles and 150-200 hydrogen fuel cell buses [1].

The main renewable sources to provide green electricity to the electrolysers in Spain are wind and solar PV. As of February 2023, 29.986 MW of wind power and 19.621 MW of solar PV are installed in the territory of Spain [2] and according to the Plan Nacional Integrado de Energía y Clima 2021-2030 the goal of the country is to have 50 GW of wind and 39 GW of solar PV power installed by 2030 [3].

In this context, hydrogen production is a way of harnessing 100% of wind and PV electricity generation in those moments when the electricity generation is greater than the demand and the electricity surplus would be otherwise wasted.

Apart from the electricity, the other key input for the hydrogen generation is pure water which is not abundant in Spain and especially in the Valencian Community. The average rainfall in the peninsula decreases from North to South and from West to East [4]. This means that the extreme southeast where the Valencian Community is close to is one of the regions with the lowest rainfall. Additionally, as one can see in Figure 1, this rainfall is stationary and there can be large periods with water availability problems. Therefore, since the water used for electrolysis must not enter in a competition against the water used for agricultural and human consumption, special attention must be paid to desalination technology with the Mediterranean Sea nearby.

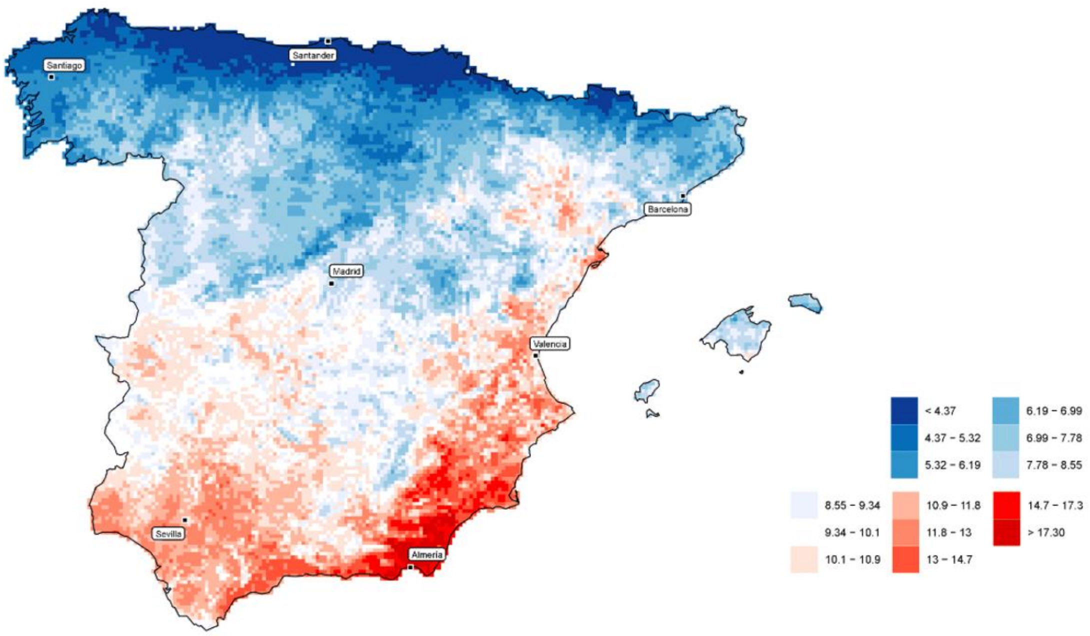

Figure 1. Average consecutive days without rainfall in Spain [5]

Nowadays there is a grey hydrogen industry already developed where hydrogen is produced from natural gas. As one can see in Figure 2, more than a half of this hydrogen globally produced (around

65%) is used in the chemical industry with the ammonia synthesis process accounting for a 55% and the methanol production around 10%.The hydrogen consumption is followed by the refining industry with a 25% and finally the remaining 10% is used by other industries such as the transport and the energy sector [6]. However, 95% of this hydrogen is grey hydrogen produced from natural gas through steam methane reforming which produces among other byproducts both carbon monoxide and dioxide [7].

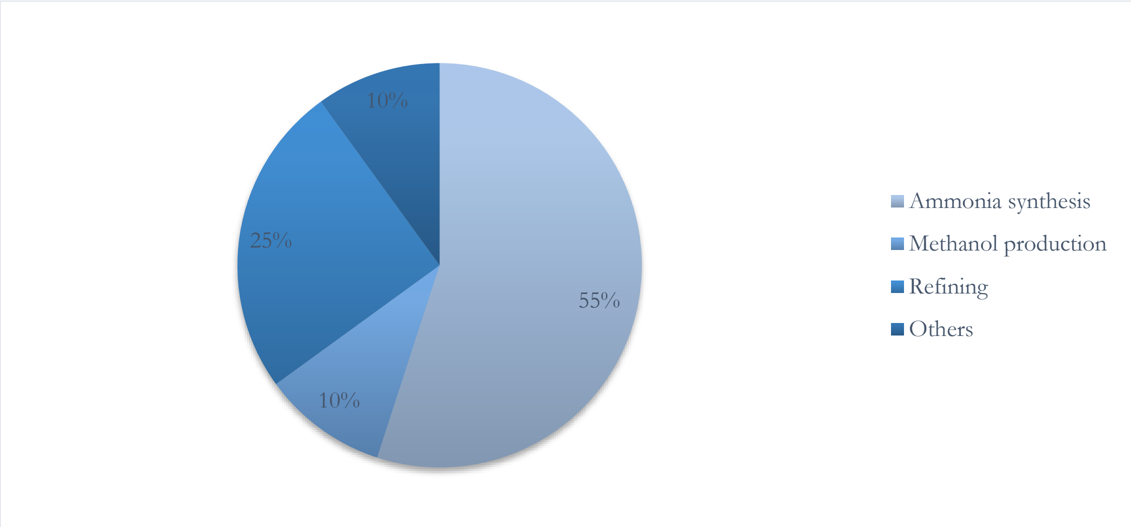

Figure 2. Hydrogen usage share per sector recreated from [6].

Following the trends of the Net zero projects being developed and having the IEA Net Zero scenario as a reference, the hydrogen demand is expected to increase from 94.3 Mt H_2 in 2021 to 179.9 Mt H_2 by 2030 as shown in Figure 3 which will mainly be green or blue hydrogen [8]. Green hydrogen is produced through the electrolysis of water with electricity coming from renewable sources such as solar or wind. Thus, there is a need of evaluating the availability of these resources and the transportation and storage options in order to deploy a proper green hydrogen industry.

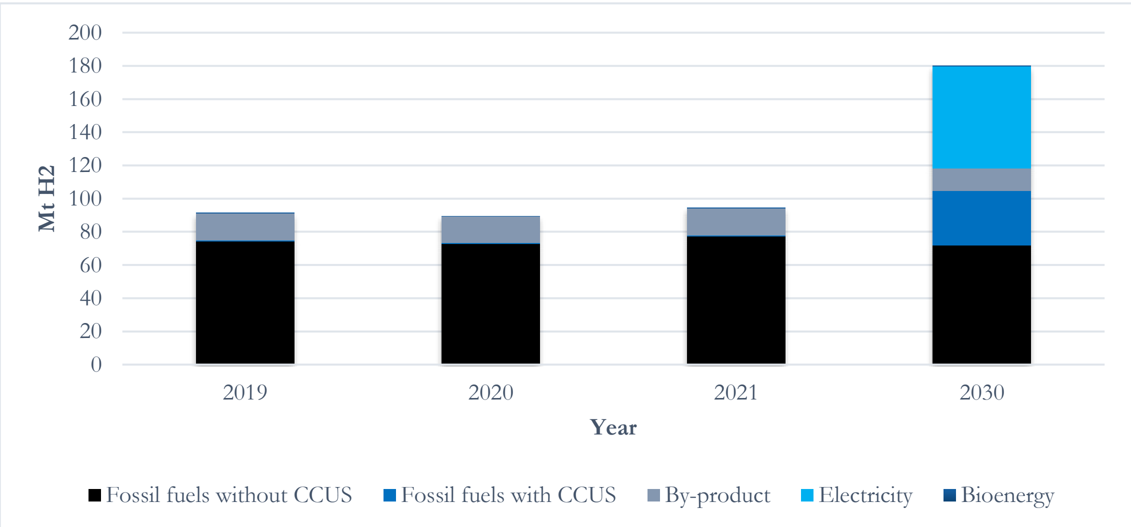

Figure 3. Hydrogen demand projection in the IEA Net Zero scenario recreated from [8].

Regarding the hydrogen transportation infrastructures in the Valencian Community, there are several possibilities. As is known, natural gas pipelines can be repurposed in order to be able to transport hydrogen [9]. The main pipelines within the Valencian Community are the “Eje-Levante” with 540 km and the “Barcelona-Bilbao-Valencia” with 2.117km [10]. Additionally, the hydrogen could be transported in a compressed gas or liquid state by road transport through the A7, AP7, E15 roads and many others which connect the main industrial points of the Valencian Community between them and with the other Spanish communities.

Through this network of pipelines and roads there are several industries where hydrogen is needed or could be a substitute for fossil fuels in energy intensive processes. Among these key industries one could highlight the biggest cargo port of the Mediterranean in Valencia, the LPG regasification plant in Sagunto, the BP refinery in Castellón and chemical and ceramic industries throughout the community [11]. The interest in the hydrogen sector of these industries within the Valencian Community resides in using the green hydrogen and oxygen produced in the electrolysis for internal processes as feedstocks or the hydrogen as fuel in the chemical and ceramic sector, green hydrogen as a fuel for the transport within the port and for the electrification of the main consumptions through the use of fuel cells. In the refinery, green hydrogen can serve as a substitute for grey hydrogen produced in their facilities. Finally, regarding mobility and the electric sector, green hydrogen could help to develop the electrification of the heavy road and maritime transport through fuel cells use and as energy storage in hydrogen form and green electricity production.

2 Research objective and questions

This research aims to develop a methodology to give a proposal of the most suitable locations of green hydrogen production facilities and their production potential and limitations by evaluating the solar, wind and water resources available within the Valencian Community as well as the transportation infrastructures and main hydrogen potential consumptions. Additionally, special attention will be given to the water allocation since hydrogen could be exported and with it, the water resources from the Valencian Community.

Thus, the research will answer the following questions:

- Which are the most suitable locations for green hydrogen production facilities within the geographical boundaries of the Valencian Community based on the available resources, infrastructures and water availability?
- What is the hydrogen production potential of the identified locations in terms of H_2 tons/year and their LCOH considering the resources available around those areas?

2.1 State of the art and research gap

In the field of green hydrogen production, the selection of optimal sites has become a critical area of research and practical application. Various methods and approaches have been developed to identify the most suitable sites for green hydrogen projects. A thorough examination of a number of important aspects is required for a state-of-the-art evaluation of this field.

The evaluation of the potential for renewable energy is a crucial component. Researchers and business professionals have identified Spanish regions with strong solar [12], wind [13], or other clean energy sources using sophisticated mapping techniques and data analysis. Taking advantage of these studies, analysis such as "GIS-based site suitability analysis for solar and wind to hydrogen potential in Europe and Mediterranean region in 2030 and 2040" [14] have been developed which seek to identify regions with the ideal conditions for green hydrogen generation by examining variables including solar radiation, wind speed, and resource availability.

When choosing a location, infrastructural accessibility and sufficiency are key considerations. Existing connections to the power grid, natural gas infrastructure, and transportation networks are all seen as crucial elements. The viability and affordability of green hydrogen projects can be considerably impacted by determining how close possible hydrogen production facilities are to these infrastructural networks [15], [16].

The availability of water is essential for producing green hydrogen. Researchers looked at the water resources' accessibility and potential rivalry with other sectors like agricultural or human consumption. Innovative technologies like desalination or water recycling have been researched in locations with a lack of water to enable sustainable water usage in hydrogen generation processes [17].

In addition to the factors already mentioned, the most suitable locations should be determined by market demand and proximity to potential customers. It will be possible to pinpoint regions with a high demand and potential application for green hydrogen by analysing industrial clusters, transportation hubs, and growing hydrogen markets.

There have been several research about green hydrogen production optimal locations that have considered many of the key aspects mentioned above such as the study "Suitable Site Selection for Solar-Based Green Hydrogen in Southern Thailand Using GIS-MCDM Approach [15]" or "A regional decision support system for onsite renewable hydrogen production from solar and wind energy sources [16]".

However, in any of these variety of studies there has been a methodology elaboration where all the factors are combined without quantifying water consumption. Specifically, there is a research gap in terms of water availability as a limitation. In their hydrogen potential production or limit, no consideration has been done regarding the water available on the site of production and neither about other sectors that may enter in competition for this scarce resource. This research will complete this missing section which is crucial in an analysis of green hydrogen production through electrolysis, water consumption and hydrogen transportation.

2.2 Scope and limitations

The research will be based on theoretical studies and mathematical models and algorithms which try to represent the behaviour of the real world. Therefore, the results may be used as an advice and they should be tested in the real world and properly interpreted by evaluating the assumptions done in the model developed.

The only production of hydrogen considered in the study is the one which comes from green electricity provided by solar photovoltaic or wind power through electrolysis. Additionally, the water used for the electrolysis must be the excess water which will not compete against the agricultural sector and human consumption.

The geographical boundaries of the study will be those of the Valencian Community. Thus, the available data regarding the resources and infrastructures of this region will be another limitation.

3 Methodology

The methodology followed in this project is presented in Figure 4 which will combine literature review and data acquisition with a techno-economic analysis of green hydrogen production in several identified locations.

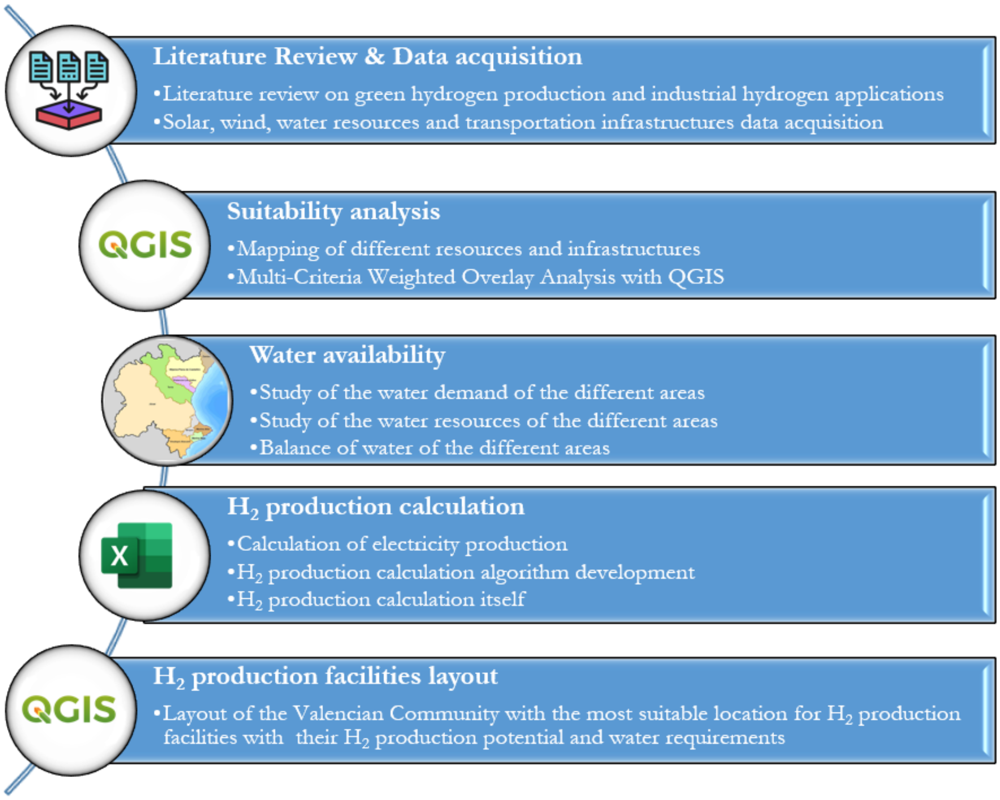

Figure 4. Detailed methodology flowchart for the study

The first step will be a literature review with data acquisition. This will include creating a map for each of the following aspects: solar, wind and water resource, infrastructures (roads/railways, airports/seaports and power lines), major urban centres, potential hydrogen consumption industries (ceramic, chemical, fertilisers, refinery and transport sector) and protected natural areas.

The created maps will be then combined and evaluated using a Multi-Criteria Weighted Overlay Analysis using the opensource QGIS software [18]. In this step each of the factors will have a weight assigned to it within a numbering scale so that the most suitable hydrogen production facilities location can be determined. In order to assign the different weights to each criteria which in this case are represented by the layers created in the first step, the Analytic Hierarchy Process (AHP) will be utilised.

Once the location of the several production facilities is set, the hydrogen production potential of them will be calculated considering all the resources present near to that facility e.g. solar, wind and water. This postprocessing of the QGIS output will be conducted by using the software Solargis [19] for the electricity production and Microsoft Office Excel for all other calculations.

Finally, an economical assessment of the different installations in each location will be performed in order to complement the mapping information with the levelized cost of hydrogen for each site.

3.1 Green hydrogen production

According to the production method and the inputs for the process, hydrogen is classified following a colour codification. Although it is not officially regulated and it can suffer several variations depending on the source, the most commonly used classification can be seen in Figure 5. Since this research is developed within a sustainable framework, the methodology will be focused only in the green hydrogen production method for having zero CO_2 emissions associated with its production process.

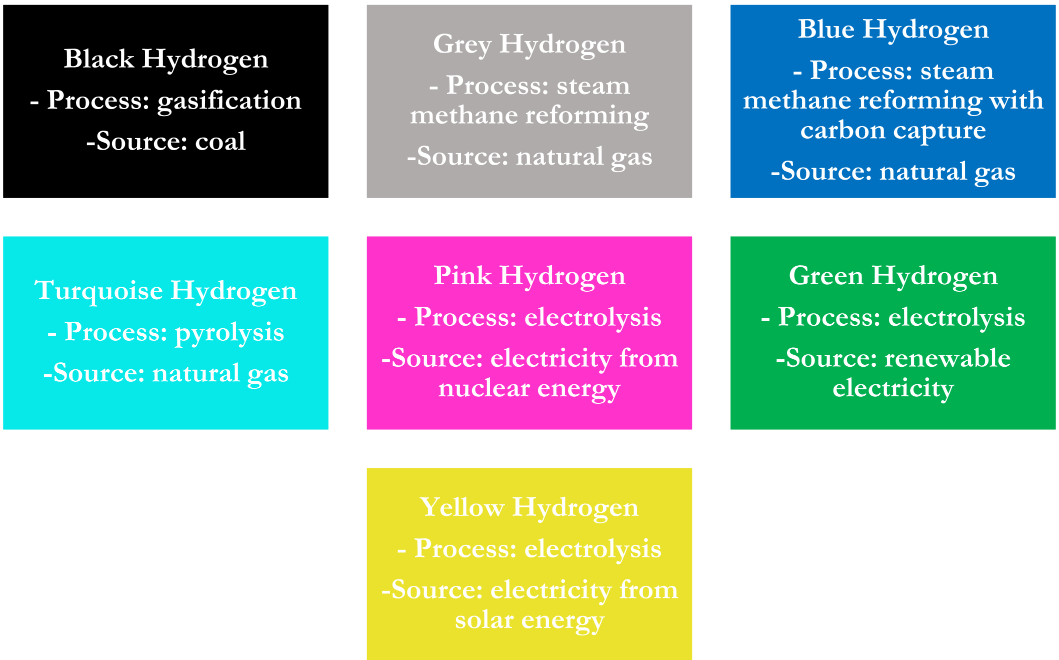

Figure 5. Hydrogen classification [20]

3.1.1 Water Electrolysis

Water electrolysis is the process in which electricity is applied to the water and as a result it is split into hydrogen and oxygen following the Equation 1.

$$H_2O + electricity \rightarrow H_2 + \frac{1}{2}O_2 \qquad (1)$$

The main component of the hydrogen production through electrolysis is the electrolyser. Depending on the electrolyte material used, there are three main types of electrolysers: Alkaline, PEM and Solid Oxide. Although it can vary depending on the electrolyser type, it mainly consists of a cathode (negative charge), an anode (positive charge) and a membrane. These three elements form the electrolysis cells that can be assembled in series together with others in cell stacks in order to produce more hydrogen and oxygen.

Alkaline Electrolyser

Nowadays, the most developed, mature and cheapest water electrolysis technology is the alkaline [21]. A liquid electrolyte is used in the alkaline electrolyser such as potassium hydroxide (KOH) or sodium hydroxide (NaOH). In the electrolyser there is a cell that is composed of a membrane, anode, and cathode where hydrogen is generated (see Figure 6). When direct current is applied to the cell, several reactions take place.

In the cathode, the water reduction takes place:

$$H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad (2)$$

While in the anode, hydroxyl ions oxidation occur:

$$2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^- \quad (3)$$

Which results in the overall reaction presented before in equation 1.

Among the alkaline electrolysers, when it comes to the position of the electrodes there are two main types: the gap cells, when the membrane and the electrodes are separated by a gap and the zero-gap cells, when there is no gap and the electrodes are directly in contact with the membrane.

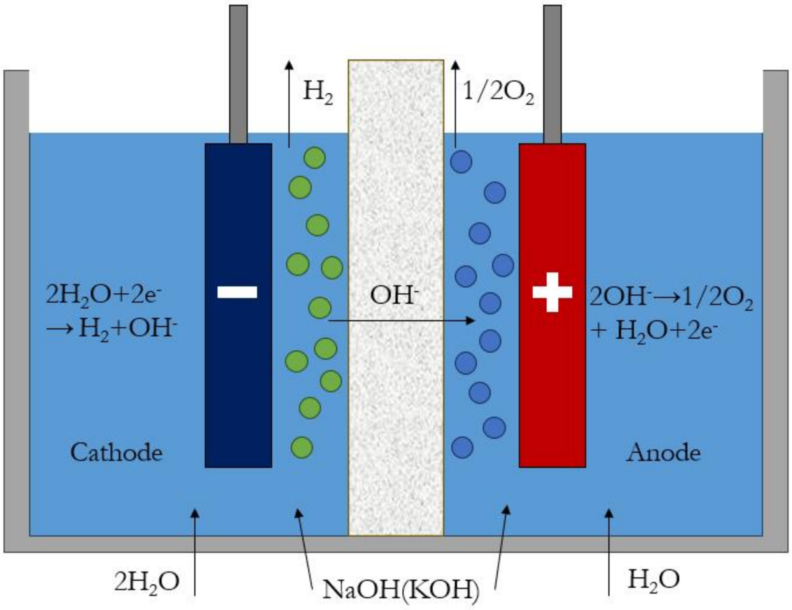

Figure 6. Alkaline electrolyser diagram [22]

Following the Ohm's law, $\Delta E_{ohm} = -I \cdot R_{cell}$, where R_{cell} is the ohmic resistance of the cell which is directly proportional to the distance between the electrodes, one can conclude that the zero-gap configuration can help reduce the ohmic drop of the electrolyser.

Commercial alkaline electrolysers usually operate at temperatures around 60 to 80ºC and pressures up to 30 bar [21].

PEM Electrolyser

In the Proton Exchange Membrane (PEM) electrolyser however, the atmosphere where the reactions happen occur is acid, and the polymeric membrane is immersed in pure water (see Figure 7).

Here, the water splits into hydrogen protons (H^+), oxygen (O_2) and electrons when direct current is applied to the cell. The membrane then allows H^+ protons to pass through it thanks to its polymeric characteristics. On the cathode side, these protons recombine with the electrons that have travelled through an external circuit, resulting in the formation of H_2 gas.

The following equation shows how the water is oxidized at the anode side forming O_2 and hydrogen protons:

$$H_2O \rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^- \quad (4)$$

After the first reaction of the electrolysis occurs, the hydrogen protons pass through the PEM and are reduced in the cathode forming H_2:

$$2H^+ + 2e^- \rightarrow H_2 \quad (5)$$

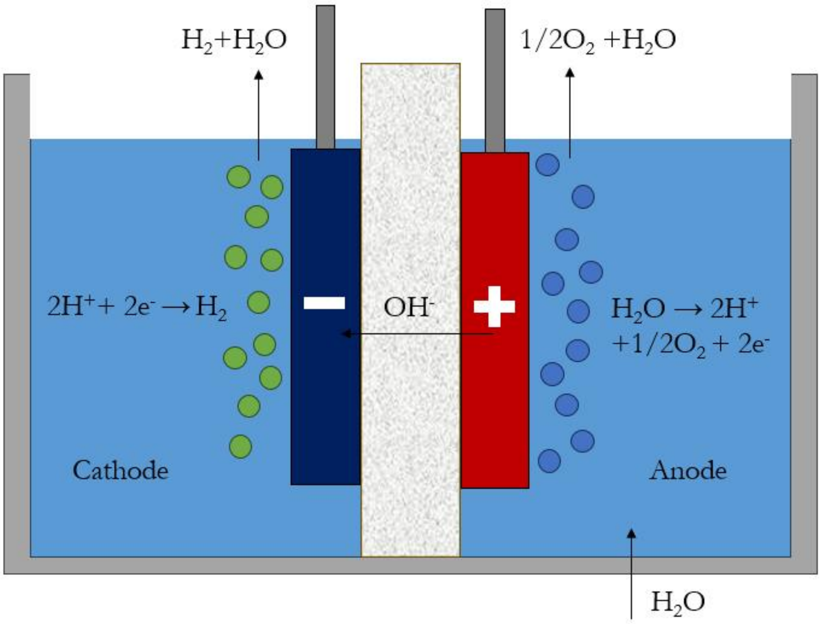

Figure 7. PEM electrolyser diagram[18]

In comparison to the alkaline electrolysers, PEM electrolysis needs slightly less power to produce the same amount of hydrogen. However, in terms of durability and reliability, they have a better performance [21].

Moreover, the nature of this type of electrolyser allows to have two pressure levels at both sides enabling the resulting H_2 to be stored already pressurized.

Solid Oxide Electrolyser

The Solid Oxide electrolyser (SOE) is the most recent technology in comparison to the previous ones and it theoretically provides the greatest energy efficiency by using a solid ceramic material as the electrolyte and performing at high temperature levels (see Figure 8).

The alkaline and PEM electrolysers are considered low temperature electrolysers while in the SOE the reactions happen at an operating range of 500 – 1000 ºC. Therefore, in this type of high temperature electrolyser steam and electricity is needed. When they are delivered, water is reduced to oxygen ions (O_2^-) and hydrogen gas is formed in the cathode as one can see in the reactions below.

Water vapor is reduced in the cathode side:

$$H_2O \; + 2e^- \rightarrow \; H_2 + O^{2-} \qquad (6)$$

Oxygen ions pass through the electrolyte to the anode side where they are oxidized:

$$2O^{2-} - 2e^- \rightarrow \; O_2 \qquad (7)$$

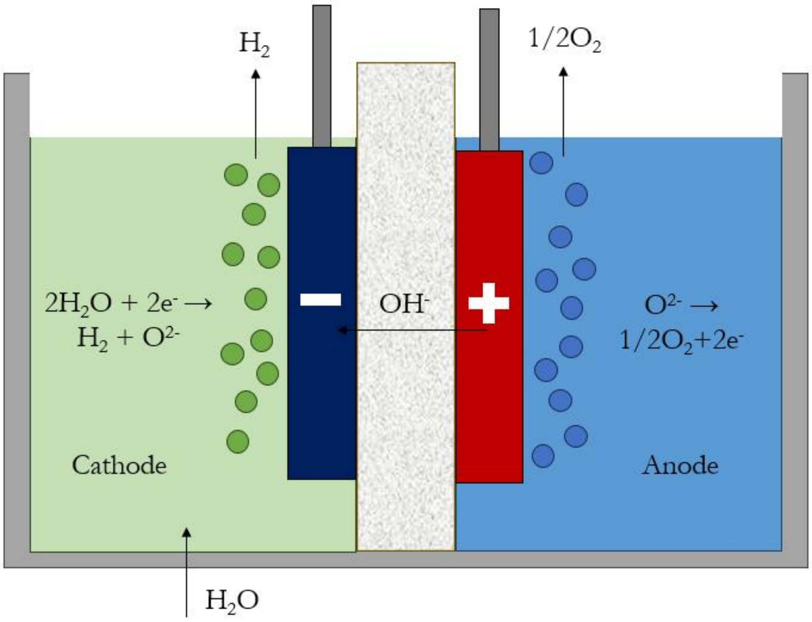

Figure 8. Solid Oxide electrolyser diagram [22]

As stated before, SOE are characterized by their oxygen ion electrolyte which requires a high operating temperature to be conductive because it is usually fabricated with yttria-stabilized zirconia (YSZ) forming a dense ceramic layer.

In order to give a general overview of the main techno-economic parameters of the presented types of electrolyzers, the summary in Table 1 has been created.

Table 1. Electrolyzers' comparison [21], [23]–[27]

Parameter	**Alkaline**	**PEM**	**SOE**
Operating temperature (ºC)	60 – 80	50 – 80	500 – 1000
Operating pressure (bar)	30	30 – 40	1 – 10
Electrolysis efficiency (%)	60 – 75	70 – 90	85 – 100
Electrolyte	20 – 30 % KOH or NaOH	Solid Polymer Electrolyte (e.g., perfluoro sulfonic acid)	ZrO_2 ceramic dopped with Y_2O_3
Capex (€/kW)	500 – 1400	1100 – 1800	2800 – 5600

3.1.2 Components for green hydrogen production

Water

The key input for green hydrogen production is pure water, which can be obtained from various sources such as rivers, swamps, ground water and sea water (particularly in the Valencian Community, the Mediterranean Sea serves as a significant water source). However, it is important to note that some of these sources may also be used for agriculture and other freshwater needs, and the use of these sources for hydrogen production should not compromise their availability for other essential purposes. Additionally, regardless of the water source, water must be purified before it goes to the electrolyser and thus, there is a need for a water treatment plant.

It is known that the electrolysis reaction follows this equation: $2H_2O \rightarrow 2H_2 + O_2$ which means that 1 mol of H_2O is required to produce 1 mol of H_2. Considering the atomic weight of each molecule:

$$1\ mol\ H_2O = 18.015\ g\ H_2O$$

$$1\ mol\ H_2 = 2.016\ g\ H_2$$

Resulting in an average water consumption rate of $\frac{18.015}{2.016} = 8.94$ kgH_2O/kgH_2

As shown in the previous calculations, the electrolysis process has a water consumption rate of 8.94 kgH_2O/kgH_2. However, this is purified and deionized water ready to be used as the input of the electrolyser. To obtain deionized water, also known as demineralized water, charged mineral ions such as calcium, magnesium, sodium or chloride must be removed by applying purification methods such as ion exchange resins or reverse osmosis. Therefore, the 8.94 rate is higher when talking about raw water from different sources such as rivers, dams or the sea.

In order to give a general overview of the water requirements and its impact in the water usage of the planet, it can be seen in this graph from [28] that if all existing fossil fuel consumption were replaced with green hydrogen, it only would be needed around 0.000006% of the seawater resource or 0.09% of the accessible fresh water as shown in Figure 9.

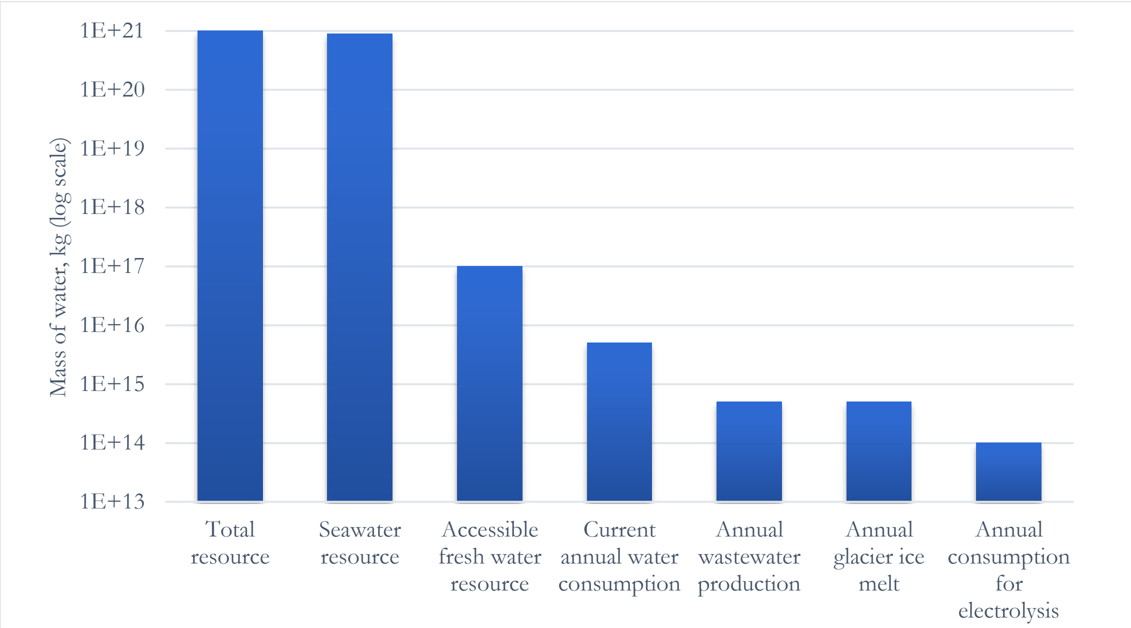

Figure 9. Annual water required for producing green hydrogen that would substitute all existing fossil fuels [28]

Water treatment

According to Nel Hydrogen, the global largest electrolyser manufacturer, the level of purified water for the electrolysis is such that may comply with the requirements at least of Type II although Type I is recommended as defined by the American Society for Testing and Materials (ASTM) [29]. This classification can be seen in Table 2.

Table 2. Requirements for water suitable for use in methods of chemical analysis and physical testing [30]

Parameter	Type I	Type II	Type III	Type IV
Electrical conductivity, max, µS/cm at 298 K (25°C)	0.056	1.0	0.25	5.0

Electrical resistivity, min, Mcm at 298 K (25°C)	18	1.0	4.0	0.2
pH at 298 K (25°C)	A	A	A	5.0 to 8.0
Total organic carbon (TOC), max, µg/L	50	50	200	No limit
Sodium, max, µg/L	1	5	10	50
Chlorides, max, µg/L	1	5	10	50
Total silica, max, µg/L	3	3	500	No limit

In order to obtain water Type I and depending on the source of the water (seawater, groundwater, etc.) and the volume required, the water treatment plant required design will vary. However, it will be composed of three main phases: pre-treatment, reverse osmosis and electrodeionization [31].

The aim of the pre-treatment phase is to optimize the water characteristics to ensure it is suitable for the reverse osmosis (RO) process. The pre-treatment will be adjusted to the characteristics and precedence of the raw water. For example, if it is used organic contaminated water, it is advisable to carry out a previous disinfection treatment to eliminate pathogens from the water, either with the addition of some type of oxidant such as chlorine or ozone. In the case of seawater, it passes through several screens to filter out seaweed and ultrafiltration processes which can even filtrate virus and bacteria.

After the water has the characteristics needed for the second phase, the reverse osmosis is performed. This process requires pressures up to 60-70 bar and when it is finished, 99% of the salts present in the water are filtrated.

Finally, in order to reach the low conductivity levels that electrolysers require, an electrodeionization (EDI) process is needed so that the remaining ions in the output water from the RO are exchanged for H+ and OH- ions.

In Figure 10, different pathways of water treatments can be seen depending on the source of the raw water utilised.

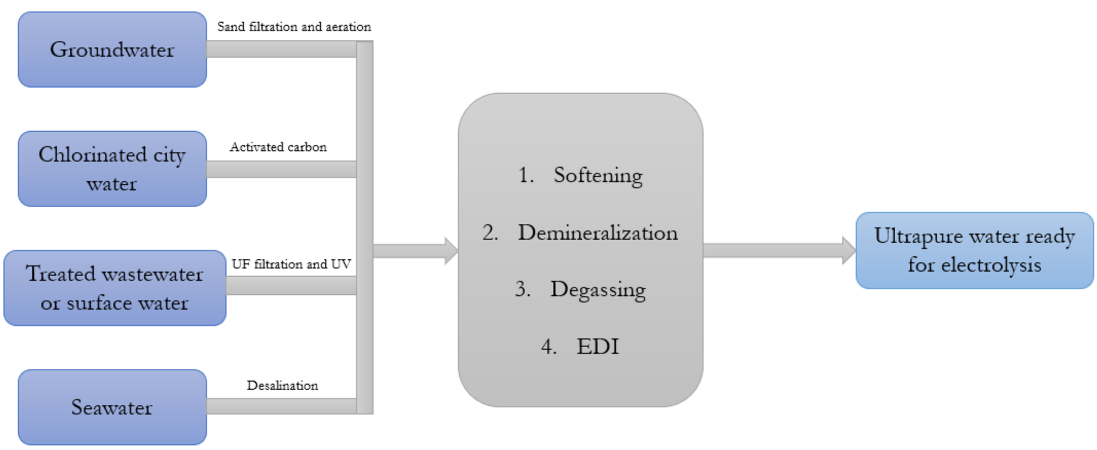

Figure 10. Water treatment pathways depending on the raw water source [32]

As one could conclude, the different pathways will have different energy consumption rates and it will require different quantities of raw water in order to obtain the same amount of purified water. According to [32], in order to purify 1 m^3 of water for electrolysis, 7 kWh of energy are required if the raw water is seawater, 2.2 kWh if it is treated wastewater and 2 kWh if it is groundwater.

Additionally, in [32] it has been concluded that it is an acceptable rule of thumb to consider 3.3 m^3 of seawater, 1.5 m^3 of treated wastewater/surface water or 1.4 m^3 of groundwater to produce 1 m^3 of ultrapure water.

Due to the geographical location of the Valencian Community next to the Mediterranean Sea, special focus will be set to seawater desalination and its requirements.

A generic desalination plant is a facility that uses a combination of several processes of different nature such as mechanical or chemical in order to remove the salt and other mineral so that it can be suitable for its electrolysis.

Its typical structure consists of several parts from which the main components are the intake facility, pre-treatment systems, reverse osmosis and distillation, and ending with some post-treatment systems.

As its name states, the intake structures capture the seawater from the sea and transfer it to the plant where the treatment starts with a removal of large particles, suspended solids and organic matter from the raw water in the pre-treatment systems. After that, the reverse osmosis is performed with high pressure pumps forcing the seawater pass through semi-permeable membranes which retain the salt and other minerals from the seawater. Then water is boiled in the distillation unit and condensed back in a different site after that in order to obtain fresh water. Finally, in the post-treatment systems the pH is adjusted as well as the mineral content.

Water demand in the Valencian Community

The Valencian Community is a region located on the eastern coast of Spain and due to its geographical location, it has a Mediterranean climate which means hot and dry summers and mild-tempered winters. Because of the growing population and its characteristic arid climate, water demand has always been a significant concern in the Valencian Community.

According to [33] the total demand of water in the Valencian Community was approximately 1070hm^3 in 2020 from which around 75% was used by the agricultural sector and the remaining 25% for residential, industrial and other uses.

Although the Valencian Community is investing in several sectors such as desalination plants, modernization of irrigation systems and water treatment, the scarcity of water is a persistent issue and hence it is important that any demand of water coming from the hydrogen production facilities does not enter in a competition against any of the sectors stated before.

Renewable electricity

The other key input for green hydrogen production is green electricity. Due to the suitability to be integrated in a green hydrogen production plant and the resources available in the Valencian Community, this electricity can be obtained from solar PV or wind.

Renewable electricity generation in Spain has been growing in detriment to the fossil fuels generation during the last 30 years. As shown in Figure 11created by the IEA, the leading technologies in the country have been wind and solar PV [34].

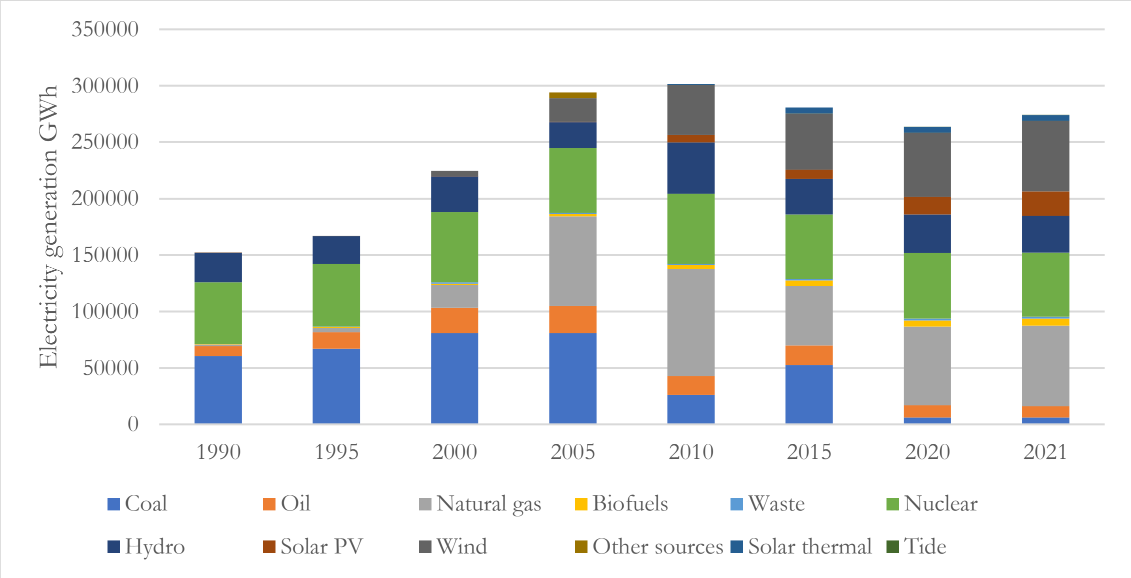

Figure 11. Electricity generation by source, Spain 1990-2021 [34]

In order to take into account all the electricity needed in the value chain of green hydrogen production, one has to consider the electricity required for the water treatment and the electrolyser.

The IEA commonly uses a parameter in its reports where the technology readiness of different technologies is assessed ranking them from 1 (small prototype) to 11 (mature). According to the IEA electrolysers report of 2022 [27], both PEM and alkaline technologies are at the same level (9) and the other technologies are still in demonstration phases (see Figure 12).

Additionally, comparing a PEM commercial electrolyser [35] and an alkaline electrolyser [36] of Cummins, a well stablished company in the water electrolysis sector, one can see that the system specific consumption of the alkaline electrolyser (55 – 60 kWh/kg) is higher than the PEM electrolyser ($\leq$ 51 kWh/kg).

When it comes to the cost-effectiveness of the electrolyzer, the one of the PEM is higher despite the higher capital costs due to its lower cost of balance of plant and complexity as the system size increases [37]. Thus, having in consideration all the previously mentioned factors, in this study the PEM electrolysis technology is selected.

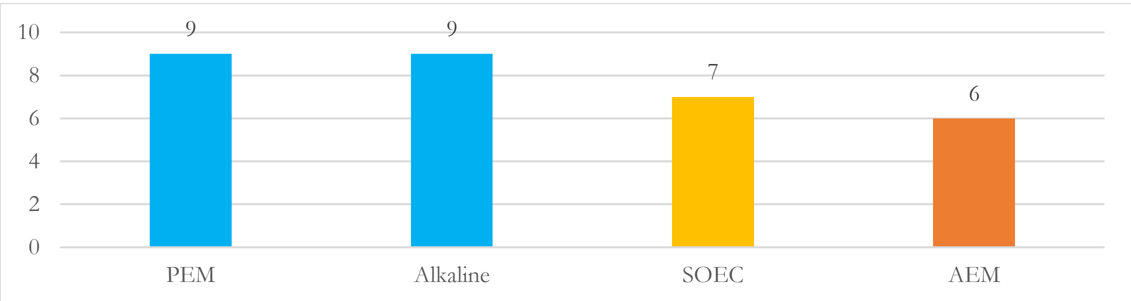

Figure 12. Technology readiness level – electrolysers [27]

Solar PV

A solar panel or photovoltaic (PV) panel comprises multiple solar cells that produce electricity by means of the photovoltaic effect, which involves three primary stages. Initially, solar radiation is absorbed and dislodges electrons from the semiconductor material, typically silicon. Subsequently, these electrons move through the two layers of the solar cell, generating an electrical current. Finally, the current is transmitted to wires and linked with other solar cells in the panel.

When it comes to a solar PV plant, there are three main parts: the solar panels or modules which as stated before are the main components of the plant combining them in series and parallel circuits in order to reach the desired current and voltage output, the mounting structures which support the solar panels and can be adjusted for the modules to track the sunlight and the inverters which convert the direct current from the modules into alternating current.

As one can see in Figure 11, Spain has seen a rapid increase in solar PV capacity and although this may be seen as a good thing, it also comes with some issues that green hydrogen could solve such as the curtailment.

Curtailment in solar PV refers to the practice of reducing or shutting down the output of solar PV power plants when the electricity demand is low or the grid is congested and according to [38], solar PV curtailment in Spain increased from 1.7% in 2018 to 2.5% in 2019 due to the insufficient capacity of the transmission and distribution network as well as the lack of excess energy storage facilities. It is important to note that curtailment data in the Valencian Community is not available but the national numbers can be used to give a general idea.

In this context, power-to-gas technology can be used to prevent solar PV curtailment. This technology involves converting excess solar energy into green hydrogen by performing the electrolysis process and storing it in tanks so that when the demand is high again it can be used to generate renewable electricity through a fuel cell.

As of October 2018, there are 600 MW of solar PV installed in the Valencian Community [39] and as outlined in its 2021-2030 energy strategy plan, the goal is to continue growing the solar PV capacity by 1000 MW by 2030, especially in the self-consumption sector.

In order to provide an order of magnitude for the solar resource in the region of study, this map generated by Global Solar Atlas is presented in the Figure 13. It shows that the global horizontal irradiation in the Valencian Community during the 1994-2018 period has varied from 1110.73 kWh/m^2 to 1817.12 kWh/m^2 yearly which is relatively homogeneous throughout the territory.

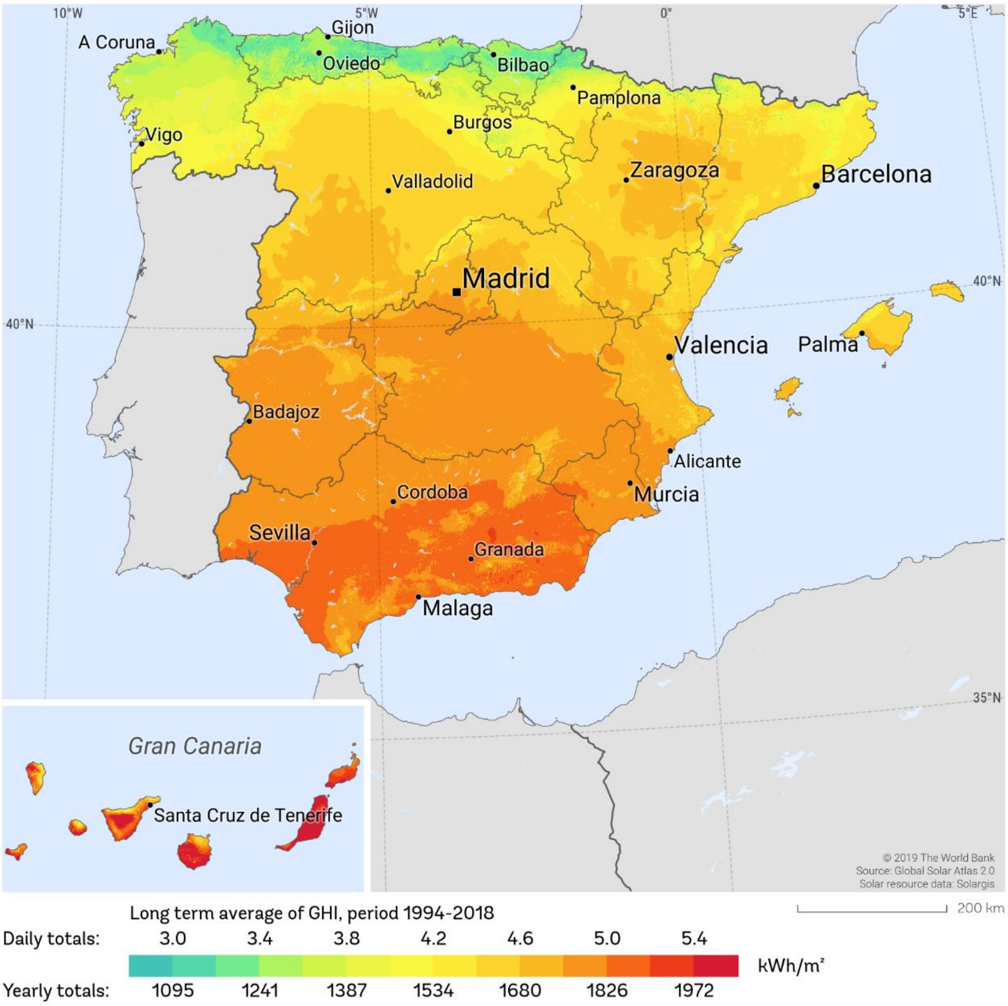

Figure 13. Global Horizontal Irradiation in Spain [40]

Wind

A wind turbine works by converting the kinetic energy of wind into electrical energy. Its basic principle is that the wind blows past its rotor blades and makes them to rotate. Since the rotor blades are connected to a central shaft, it turns an electricity generator which produces more electricity the faster the wind blows/the rotor blades spin. This electricity is in the form of alternating current which must be converted into direct current to stabilize it since the wind does not blow at a constant velocity.

The wind turbine is usually equipped with a control system which allows to optimize its performance and ensure its safety. Additionally, a tower supports the wind turbine and raises it to a height where it can capture the most wind.

As of October 2018, there were around 1700 MW of wind power installed in the Valencian Community [39]. According to [41], this power is distributed among 36 wind farms. One of the largest wind farms in the region is the Cofrentes Wind Farm, located in the province of Valencia, which has an installed capacity of 50 MW.

Similar to solar PV, wind power in Spain has increased a lot during the last decades and the national grid was not adequately equipped to handle this sudden surge in power supply from wind energy sources all at once. Therefore, curtailment also occurs in the Spanish wind power sector. Although there is no specific data for the curtailment in the Valencian Community, it is worth to mention that according to the Spanish Wind Energy Association (AEE) [42], curtailment in Spain in 2019 reached

3.8% which could be reduced with green hydrogen production as a way of harnessing the excess of energy.

Regarding the Valencian Community plans for the wind power deployment in this region, the 2021-2030 energy strategy plan states that the goal is to have a total wind power installed capacity of 4000 MW by 2030.

When it comes to electricity generation from wind, a very useful parameter to look at is the mean power density of the wind at 100 m since higher mean power density means better wind resources. The Global Wind Atlas shown in Figure 14, in the Valencian Community there is a mean power density that can reach from 26.29 W/m² to 3624.4 W/m² which gives a general overview of the great difference of wind potential in different regions of the Valencian Community.

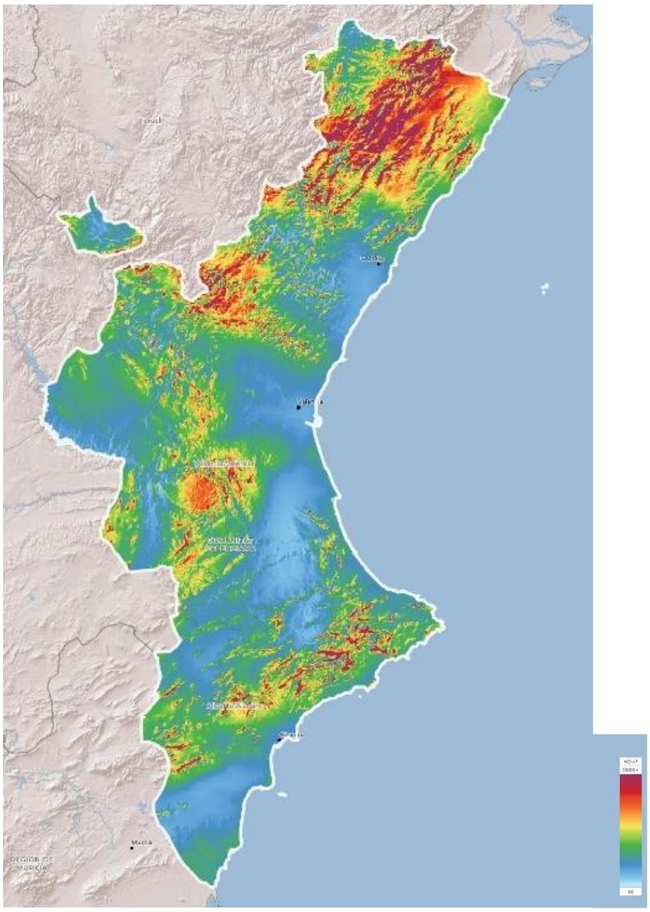

Figure 14. Mean Power Density @ 100m in the Valencian Community [43]

3.2 Hydrogen demand and potential opportunities

In this section, the different industries that currently consume hydrogen will be presented as well as the sectors which could substitute their fossil fuels consumption with green hydrogen, especially in the Valencian Community.

According to [8], the global hydrogen demand as of 2021 was 94.3 Mt H_2 distributed among the sectors as shown in Figure 15.

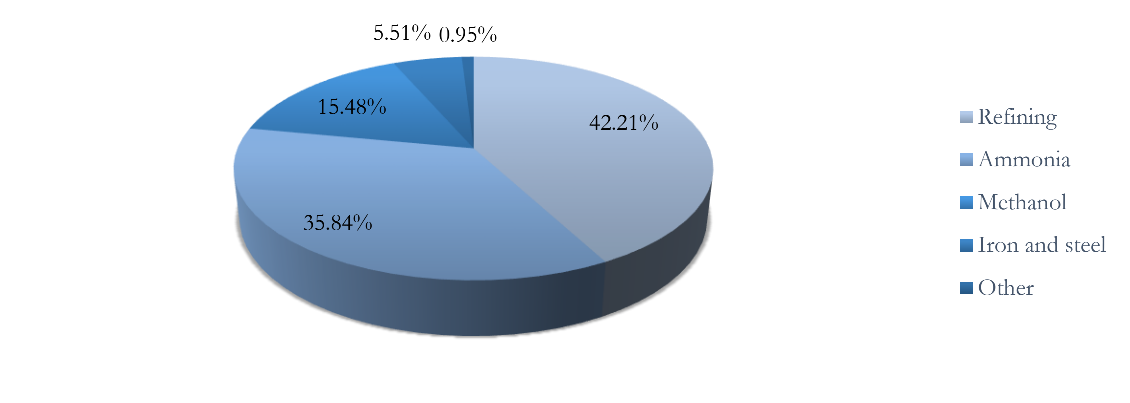

Figure 15. Global hydrogen demand by sector. Recreated from [8]

However, in the Spanish industry, the demand is clearly led by the refining sector with a 70% share of the 500,000 tons H_2 consumed in the country in 2020, followed by the chemical industry with a 25% share, and the remaining 5% distributed among other sectors such as the metallurgical industry [44].

The main applications of hydrogen in refineries are in processes to remove impurities from crude oil (hydrotreating) or to upgrade heavier crudes (hydrocracking) for use as feedstock.

When it comes to the chemical industry, due to its molecular composition, hydrogen is used as a raw material for the production of chemical products, especially ammonia and methanol, which require large quantities of hydrogen and which in turn serve as a source for the production of other chemical compounds such as fertilizers, biofuels or plastics.

Finally, in the metallurgical industry, for the production of certain alloys such as steel, large energy inputs are needed, and renewable hydrogen could be used as an energy source to reach the required temperatures in the production process (blast furnaces). It can also be used as a reducing agent for alloy generation, displacing the use of coal.

Furthermore, hydrogen exhibits great potential for use in various application within the transport sector.

The application of renewable hydrogen in the transport sector is materialized in the use of hydrogen fuel cells (FC), which are devices in which a process is carried out in reverse to that carried out by electrolysers, i.e. they use the hydrogen produced from renewable sources to generate electricity, providing the required energy to drive fuel cell electric vehicles (FCEVs). These fuel cells are usually installed in combination with electric batteries that recharge themselves during vehicle operation either during the regenerative braking process or through the battery itself, which can produce energy for recharging and maintain it at optimum charge levels.

The use of fuel cells combined with batteries in vehicles (FCHV) provides a significant competitive advantage over battery electric vehicles in heavy-duty vehicle segments, allowing shorter refuelling times and increasing the distance travelled by the vehicle before refuelling [45]. Although it depends on the model, the weight of the FCHV is generally lower by reducing the size of the batteries. However, the energy efficiency of these vehicles is lower than that of battery electric vehicles, as the energy consumed to obtain the renewable hydrogen, as well as that needed to compress and store it in the vehicle tanks, must be taken into account.

The current status for each of the options in the mobility sector in Spain is detailed below.

Road transport involves both light vehicles (passenger cars and vans) and heavy vehicles (trucks and buses). In the case of Spain, the hydrogen sector is still being introduced in the light and heavy road transport. According to [46], as of October 2021 there were 15 fuel cell vehicles while in the rest of

Europe this number was around 2400. With respect to heavy-duty vehicles, it is positioned as the segment where the use of renewable hydrogen as a fuel is most suitable. On a national scale, several pilot programmes are being carried out to analyse the feasibility of using renewable hydrogen in industrial vehicles such as forklift trucks, as well as in buses and lorries. Among them is purchase of 8 hydrogen fuel cell buses in 2020 by Transports Metropolitans de Barcelona (TMB) to the Portuguese company Caetano Bus which started to road in May 2022 [47].

Regarding rail transport, it currently uses electricity as its main energy source, although there are still unelectrified tracks with trains powered by diesel locomotives. It is interesting in this latter type of trains when electrification is not viable, where renewable hydrogen could have a clear application. To develop this alternative in Spain, Renfe, in collaboration with Enagás and the National Hydrogen Centre, has initiated a project supported by the EU to carry out tests in the test tunnel of the Barredo Foundation in Anes (Siero) [48].

Another hard-to-abate mobility sector is the maritime transport. The application of renewable hydrogen for maritime transport encompasses not only the use of fuel cells in ships, but also in the machinery used in ports and cargo terminals. In relation to ships, the use of fuel cells for maritime transport is currently limited to demonstration projects on small vessels, but feasibility analysis is expected for large vessels. In Spain, the H2Ports initiative stands out, dedicated to the development of a pilot project located in the Port of Valencia to incorporate hydrogen in port logistics operations with the aim of reducing their environmental impact. The H2Ports project has received funding from the Fuel Cells and Hydrogen Joint Undertaking (FCHJU) and has the participation of the Port Authority of Valencia, the Valenciaport Foundation, the National Hydrogen Centre and private companies [49].

Finally, fuel cells in aviation are expected to provide an alternative means to power propulsion for aircrafts and for the machinery used in airports and cargo terminals like in the shipping sector. At present, only demonstration projects have been developed for use in non-commercial flights. In Spain, ITP Aero is expected to start conducting the first tests of a hydrogen engine for aircraft in 2025 [50]. Furthermore, in the aviation sector, the application of renewable hydrogen for the production of synthetic fuels, such as biokerosene, is particularly relevant.

As one can conclude, apart from hydrogen hubs in seaports, airports and train stations, an opportunity for hydrogen consumption arises in the form of establishing hydrogen refuelling stations (HRS) along the main roads of the Valencian Community. These HRSs would be specifically designed to cater to the needs of heavy road transport vehicles.

After having discussed the potential green hydrogen demand in the transport sector, in Table 3 the identified potential green hydrogen consumers of the industrial sector in the Valencian Community are listed together with their location. For more detailed geographical location see Figure 40.

Table 3. Green hydrogen potential consumers

Company	Sector	Location
BP Oil Refinery	Oil refining	Castellón
UBE	Chemical/Plastic	Castellón
Pamesa Cerámica SL	Ceramics	Onda
Porcelanosa	Ceramics	Vila-real
Argenta Cerámica SL	Ceramics	Vall d'alba

Azulmed SL	Ceramics	Chilches
Baldocer SA	Ceramics	Vilafamés
Spanish Tiles From Nules S.A.	Ceramics	Nules
Tau Cerámico SL	Ceramics	Castellón
Keraben Group SA	Ceramics	Nules
Kerajet SA	Ceramics	Almazora
Torrecid SA	Ceramics	Alcora
Venis Projects	Ceramics	Vila-real
Halcón cerámicas SA	Ceramics	Alcora
Fertiberia	Fertilisers	Puerto de Sagunto
Compo Expert Spain SL	Fertilisers	La vall d'uixo
Antonio Tarazona SL	Fertilisers	Silla
Plastic Omnium	Chemical/Plastic	Almussafes
SP Berner Group	Chemical/Plastic	Aldaia
Dupont Nutrition And Biosciences Ibérica Sl	Chemical/Plastic	Silla
Guzman Polymers SL	Chemical/Plastic	Valencia
Mario Pilato Blat SA	Chemical/Plastic	Cheste
Sipcam Inagra SA	Chemical/Plastic	Sueca
Gazechim Composites Ibérica SA	Chemical/Plastic	Picassent
Biocom Energía	Chemical/Plastic	Algemesí

3.3 Hydrogen transportation

Once the hydrogen is produced, it is important to evaluate how it will be transported to the demand site. This section will delve into the topic of hydrogen transportation, encompassing both road and rail transportation. Furthermore, it will explore the significance of ports in facilitating hydrogen transportation, as well as the role of pipelines in transporting hydrogen.

3.3.1 Road and rail transportation

Hydrogen can be transported by road and rail either liquified or as a pressurized gas. The most common way to do it is by filling standardized vessels that can fit in hydrogen tube trailers. The Spanish company Calvera Hydrogen has developed several commercial tube trailers for hydrogen transportation that can handle up to 517 bar and transport over 1300 kg of H_2 [51].

Liquified hydrogen is also possible to transport via trucks. However, it is really challenging due to the large quantities of flammable gas that the truck would carry and the difference of temperature between the ambient and the vessel. When the destination site has been reached, leakages could happen at the moment of the transfer and hence expansion and pressure increase, risk of rupture and fire and explosion hazard. Moreover, hydrogen gas transportation is more cost-effective than liquified hydrogen due to the additional energy needed to cool it down to around – 253ºC (3.3 kWh/kgH_2) in comparison to the 1.05 kWh/kgH_2 needed to compress gas hydrogen from 20 bar to 350 bar [52] and the special cryogenic tanks required.

Rail transportation for hydrogen is very similar to the road transportation with trucks previously described but with the advantage that it can be scaled up easily. This is because the space available in the train would not be heavily penalized by having high-pressure tanks on board the train.

From what has been stated, one could argue that it is interesting to have the green hydrogen production facility near the most relevant roads and railways of the Valencian Community.

3.3.2 Maritime transportation

The transport of hydrogen across the sea can be performed in a similar way as the liquified natural gas maritime transportation. However, in order to make this way of transportation cost-effective, several conditions must be present such as the need of high-volume transport and the presence of hydrogen pipelines [53].

In order to liquify hydrogen, temperatures of – 253ºC must be reached and it involves a series of challenges. The most critical among these challenges is the substantial amount of energy required for the liquefaction process (equivalent to over 30% of the energy content of the liquefied hydrogen) and the potential occurrence of "boil-off."

Nevertheless, Kawasaki Heavy Industries[1] has developed a liquified hydrogen carrier composed of four tanks of 40,000 m^3 each, which means around 10,000 tons of LH_2 in one whole carrier (see Figure 16).

Figure 16. Simulated appearance of the completed 160,000 m3 liquefied hydrogen carrier [54]

The hydrogen maritime transportation has a certain importance in the Valencian Community since there are several ports that are relevant in a global and national level. Especially, the port of Valencia, ranking among the top 30 in the world [55] and the top 4 in Europe [56].

[1] Kawasaki Heavy Industries Ltd., https://global.kawasaki.com/?wovn=es Kawasaki Heavy Industries is a multinational corporation based in Kobe, Japan, with diverse operations in heavy machinery, aerospace, rolling stock, and energy-related products.

Figure 17 shows the key ports of Spain including those located in the Valencian Community, such as the ports of Castellón, Sagunto, Valencia, Gandía and Alicante. The image shows recreational as well as industrial seaports. While in the first hydrogen could be used to power the ship, the industrial seaports such as Castellón or Valencia can play a hydrogen delivery site role as well.

Figure 17. Ports in Spain [57]

3.3.3 Pipelines network

Currently, the predominant transportation infrastructure for hydrogen primarily focuses on connecting refineries and large chemical plants, rather than serving other energy-intensive industries or residential consumers. Consequently, the development of a well-defined strategy becomes essential for establishing a pipeline network dedicated to hydrogen transportation.

One option is to build a hydrogen pipeline network from scratch that would cover all the demand sites. Currently, the H2Med is being developed and it involves the construction of a network of pipelines around the Spanish territory and one principal pipeline through all the Valencian Community. The H2Med is a project developed by Spain, Portugal and France that aims to connect the three countries as shown in the figure below.

Figure 18. H2Med layout and other hydrogen pipelines [58]

The other alternative is blending hydrogen in the natural gas network. This process consists of introducing a percentage of hydrogen into the existing natural gas network so that the carbon intensity of the methane can be reduced.

Depending on the concentration of hydrogen that is blended in the network, pipelines might need some retrofitting to make this option technically possible. Retrofitting pipes for hydrogen transportation is a costly process due to several factors such as material compatibility requirements, higher safety measures and standards and infrastructure modifications such as compressors, pumps or valves. However, when the concentration in volume of hydrogen is lower than 10%, these retrofitting actions can be performed in an affordable way [59].

Blending is already regulated in some European countries where a limit to the concentration of hydrogen by volume is set. As shown in Figure 19, this limit is 5% in the natural gas network of Spain depicted in Figure 20.

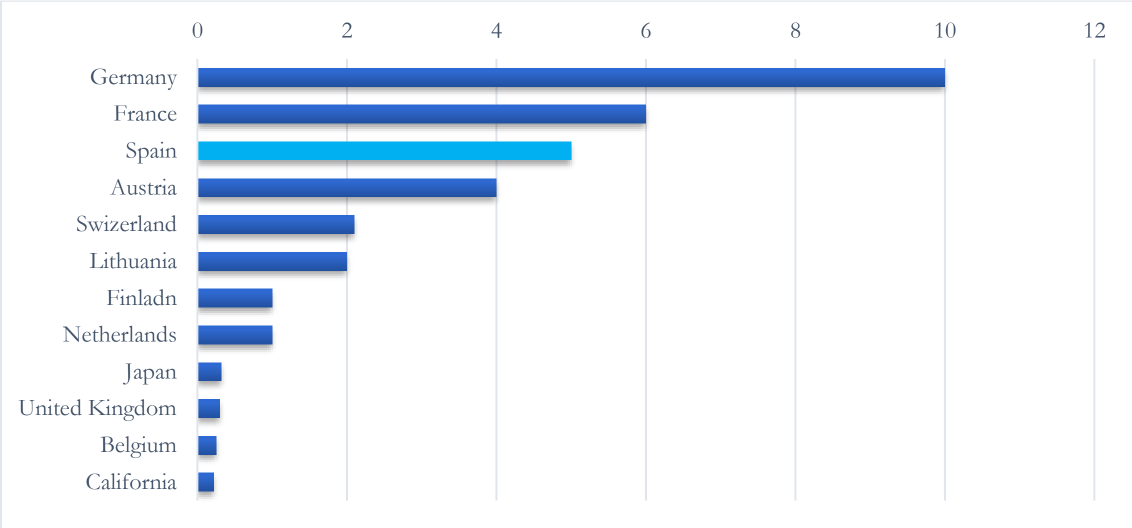

Figure 19. Limits on hydrogen blending in natural gas networks in % [60]

Figure 20. Spanish natural gas network [61]

After having covered the life cycle of green hydrogen from its production to its potential demand as well as its transportation from the generation to the consumption site, in the next chapter it is presented the methodology followed for the site suitability study.

3.4 Multi-criteria weighted overlay analysis

In the area of spatial decision making, among the most widely adopted methods one can find the Multi-criteria weighted overlay analysis [62] which is used to assess the suitability of different sites based on multiple criteria. This methodology allocates weights to each criterion showing their relative importance which afterwards are used to overlay different layers of geographic information resulting in an integrated map that illustrates locations of high suitability.

3.4.1 Weighted value estimation to study layers using AHP method

In a Geographic Information System, the fundamental component used to represent, organize and analyze spatial data is known as a layer. The geographic information in a layer can have different representations such as points, vectors, polygons or rasters.

In this methodology, 11 layers have been considered enough to represent every factor influencing the green hydrogen production site selection. Additionally, all of them are rasters or vectors transformed to rasters in order to perform a layers' overlay. While vectors are used for linear features with variable precision, rasters represent data in a grid structure with fixed resolution. Firstly, we can find three layers directly related to the potential renewable electricity production. One representing the global horizontal irradiation of the region, one representing the wind power density and one representing the proximity to power lines.

Secondly, several layers aiming to give importance to the possible hydrogen transportation and/or consumption. These are the proximity layers to roads, railways, seaports and airports.

Thirdly, potential consumption sites have been considered by using proximity layers to major urban centres and industrial clusters.

Additionally, these layers have been complemented with a proximity layer to protected areas to include the criteria of being far from these sites.

Finally, the water resource has been included in the study with a layer of proximity to water bodies and desalination plants.

When applying an MCDA approach to a study, the Analytic Hierarchy Process is commonly performed [63] when assigning different weights to each criterion. In this case the different criteria are linked to each layer after which, they will be processed in an overlay.

In order to use the AHP, pairwise comparisons are needed, i.e. judging the main layers or criteria in pairs considering the relative importance between them. Pairwise comparison matrix is developed with reference to the Saaty's scale of importance presented in the Table 4 below.

Table 4. Hierarchy fundamental scale [64]

Intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment slightly favour one activity over another
5	Essential or strong importance	Experience and judgment strongly favour one activity over another
7	Very strong importance	An activity is strongly favoured, and its dominance demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation

2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals	If activity i has one of the above numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining n numerical values to span the matrix

According to the comparison of their relative importance, the resulting pairwise comparison matrix in Table 5 is set. This matrix is a square matrix where the rows and columns represent the criteria identified with an n x n size where n is the number of layers being compared.

The pairwise matrix is filled by performing pairwise comparisons of the layers. Each cell of the matrix represents the relative importance of the corresponding row layer compared to the column layer. It is important to note that since the diagonal cells represent self-comparisons, they are given a value of 1. Additionally, in order to make sure that the judgements have been done consistently the values of the cells must be reciprocal i.e., if a value is allocated to represent importance of layer A over layer B, the reciprocal value is assigned to represent the importance of layer B over layer A.

As it can be depicted, the higher level of importance has been given to the layers representing the key resources i.e. water and renewable electricity. Between them, proximity to water bodies has been considered to have more importance since it is the main input of the electrolysis and more difficult to obtain than renewable electricity. Although the power lines can be a source of renewable electricity for the electrolysis, it has been considered to be at a lower level of importance due to their homogeneous distribution among the region. It is worth to mention that the proximity to major urban centres is at a similar level as the power lines since it is not a key factor but a good complement to make a deeper distinction between resembling sites.

At another level of importance we can find the proximity to roads and railways and the proximity to seaports and airports. In this stage seaports are set over airports due to their higher potential demand within their infrastructures and readiness level of hydrogen-fuelled ships (over hydrogen-fuelled aircrafts). When it comes to roads and railways, the potential of the first one can be set in every kilometre while in the railways it is only important in those with electrification difficulties and hence the importance level of roads is quite higher than that of being close to railways. Here it is important to note that the proximity to industrial demand is in a slightly lower importance level than the proximity to roads since the latter implies proximity to both hydrogen transportation and consumption and the industrial demand only implies consumption.

Finally, the distance to protected areas has been set in a lower scale than the key resources and demands (seaports and industrial demand) but higher than the rest of layers. This is due to its importance in not affecting the environment and facilitating the permitting activities when developing the project but at the same time not making this factor too restrictive without a real argument.

Table 5. Pairwise comparison matrix

	GHI	Wind power density	Proximity to roads	Proximity to railways	Proximity to seaports	Prox. to airports	Prox. to waterbody	Prox. to major urban centres	Prox. to power lines	Proximity to industrial demand	Distance to protected areas
GHI	1.00	1.00	6.00	7.00	5.00	8.00	0.50	8.00	9.00	3.00	3.00
Wind power density	1.00	1.00	6.00	7.00	5.00	8.00	0.50	8.00	9.00	3.00	3.00
Proximity to roads	0.17	0.17	1.00	3.00	0.33	3.00	0.25	4.00	5.00	2.00	3.00
Proximity to railways	0.14	0.14	0.33	1.00	0.25	3.00	0.17	2.00	2.00	0.20	0.25
Proximity to seaports	0.20	0.20	3.00	4.00	1.00	4.00	0.20	5.00	7.00	1.00	2.00
Proximity to airports	0.13	0.13	0.33	0.33	0.25	1.00	0.14	2.00	2.00	0.33	0.25
Proximity to waterbodies	2.00	2.00	4.00	6.00	5.00	7.00	1.00	7.00	9.00	5.00	4.00
Proximity to major urban centres	0.13	0.13	0.25	0.50	0.20	0.50	0.14	1.00	200	0.33	1.00
Proximity to power lines	0.11	0.11	0.20	0.50	0.14	0.50	0.11	0.50	1.00	0.20	0.25
Proximity to industrial demand	0.33	0.33	0.50	5.00	1.00	3.00	0.20	3.00	5.00	1.00	2.00
Distance to protected areas	0.33	0.33	4.00	4.00	0.50	4.00	0.25	1.00	4.00	0.50	1.00

Before obtaining the eigenvector, which is the scale of the different criteria, one should assess the consistency of the pairwise comparison matrix built. The consistency ratio (CR) is calculated following equations (8) and (9) and, in order to ensure a proper consistency of the AHP matrix, it should be below 10%.

In order to calculate the eigenvalues, the normalized pairwise comparison matrix must be calculated before which can be seen in Table 6

Table 6. Normalized pairwise comparison matrix

0.1806	0.1806	0.2342	0.1826	0.2677	0.1905	0.1444	0.1928	0.1636	0.1811	0.1519
0.1806	0.1806	0.2342	0.1826	0.2677	0.1905	0.1444	0.1928	0.1636	0.1811	0.1519
0.0301	0.0301	0.0390	0.0783	0.0178	0.0714	0.0722	0.0964	0.0909	0.1207	0.1519
0.0258	0.0258	0.0130	0.0261	0.0134	0.0714	0.0481	0.0482	0.0364	0.0121	0.0127
0.0361	0.0361	0.1171	0.1043	0.0535	0.0952	0.0577	0.1205	0.1273	0.0604	0.1013
0.0226	0.0226	0.0130	0.0087	0.0134	0.0238	0.0412	0.0482	0.0364	0.0201	0.0127
0.3612	0.3612	0.1561	0.1565	0.2677	0.1667	0.2887	0.1687	0.1636	0.3018	0.2025
0.0226	0.0226	0.0098	0.0130	0.0107	0.0119	0.0412	0.0241	0.0364	0.0201	0.0506
0.0201	0.0201	0.0078	0.0130	0.0076	0.0119	0.0321	0.0120	0.0182	0.0121	0.0127
0.0602	0.0602	0.0195	0.1304	0.0535	0.0714	0.0577	0.0723	0.0909	0.0604	0.1013
0.0602	0.0602	0.1561	0.1043	0.0268	0.0952	0.0722	0.0241	0.0727	0.0302	0.0506

After that, the principal eigenvalue (λ_{max}) is obtained by:

- Calculating the average vector which corresponds to the average value of each row.
- Multiplying it by the principal matrix
- Dividing the resulting vector by the average vector. The maximum value of this vector is the principal eigenvalue.

In this case, $\lambda_{max} = 12.4888$

Once the principal eigenvalue is obtained, there are two steps remaining for calculating the consistency ratio:

- Calculating the consistency index. $C.I. = \frac{(\lambda_{max} - n)}{(n-1)} = \frac{12.4888-11}{11-1} = 0.1488$ (8)
- Calculating the consistency ratio per se. $C.R. = \frac{C.I.}{R.I.}$ (9)

Where RI is the random consistency index, which can be obtained from Table 7 with reference to the number of criteria/layers (n).

Table 7. Random consistency index table [64]

n	1	2	3	4	5	6	7	8	9	10	11
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51

$$C.R. = \frac{C.I.}{R.I.} = \frac{0.1488}{1.51} = 9.86\% < 10\%$$

After checking that the matrix has an acceptable consistency ratio (CR<10%), it is time to find the eigenvector of the pairwise comparison matrix. One method to obtain the eigenvector is computing the square of the principal matrix, summing the values of each row and normalizing the resulting vector several times until the resulting eigenvector has the first four decimals as the previous iteration.

In this case it took four iterations to obtain the following weighted scale presented in Table 8:

Table 8. Weighted layers scale

GHI	0.1943
Wind power density	0.1943
Proximity to roads	0.0702
Proximity to railways	0.0269
Proximity to ports	0.0828
Proximity to airports	0.0217
Proximity to waterbodies	0.2343
Proximity to major urban centres	0.0228
Proximity to power lines	0.0141
Proximity to industrial demand	0.0674
Distance to protected areas	0.0711

3.4.2 Multi-Criteria Weighted Overlay Analysis in GIS

In order to perform the Multi-Criteria Weighted Overlay analysis in GIS software, the open source QGIS software has been used. The steps followed are summarized below.

1. Data collection. The first step of the analysis is to collect the data of all the criteria and transfer it to georeferenced layers. In some cases such as GHI the data is already georeferenced in a map and in some cases such as the seaports location the layer/map is created from scratch.
2. Layers preprocessing. As one can see in Table 9, some layers are in vector format and some in raster grid format. Moreover, these rasters can be in different scales and have different boundaries. Therefore, in order to overlay them it is firstly necessary to adequate their format transforming the vectors into rasters and reclassifying the rasters' information following the scales of Table 12 to make all the layers compatible.
3. Layers' weighted overlay. Once all the layers are compatible, they are overlayed with the assigned weights in a resulting suitability map.

Data collection

All the required data has been collected performing a literature review. The information of it has been summarized in Table 9.

Table 9. Data description

Data Layer	Format	Source
GHI	Raster grid	[40]
Wind power density	Raster grid	[43]
Road map	Vector	[65]
Railway map	Vector	[65]
Airports location	Vector	[65]
Seaports location	Vector	Google Earth research
Waterbodies	Vector	[65]
Desalination plants location	Vector	Google Earth research

Natural protected areas	Vector	[65]
Major urban centers	Vector	[65]
Power lines	Vector	[65]
Industrial demand sites	Vector	Google Earth research

After collecting the data, almost all of it needed to be processed and modified to make it adequately suitable for a proper overlay analysis. This is, adapt all the layers to make them compatible and avoid format, size, scale or boundaries issues.

Layers preprocessing

Global Horizontal Irradiation

As stated in section 4, in the Valencian Community there has been a yearly average of global horizontal irradiation during the 1994-2018 period which ranges from 1110.73 kWh/m^2 to 1817.12 kWh/m^2 yearly. This information is collected in a raster extracted from [40] where each pixel with a 0.0025x0.0025 size contains the GHI value as seen in Figure 21.

However, in order to make it comparable to the other layers once the multicriteria overlay analysis is performed, this raster is reclassified following the ranges stated in Table 12 resulting in Figure 22.

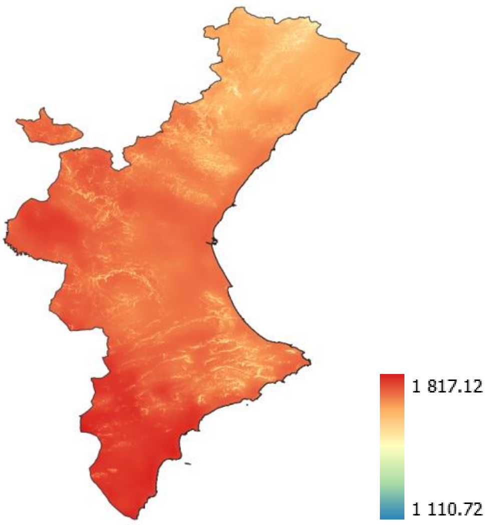

Figure 21. GHI raster (kWh/m^2)

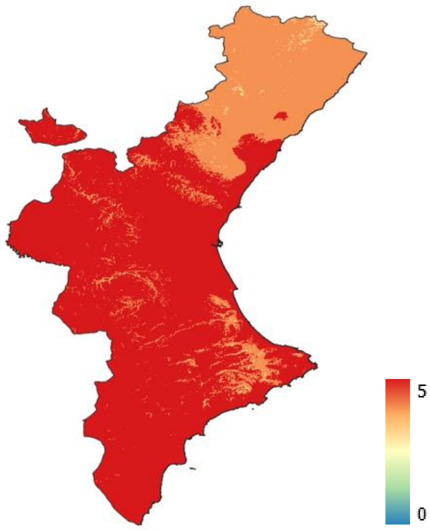

Figure 22. GHI reclassified raster

Wind power density

In order to preprocess the wind power density layer, a similar process is applied. The raster obtained from [43] has values which ranges from 26.29 W/m^2 to 3624.4 W/m^2 as seen in Figure 23.

Therefore, the raster is reclassified following the scale summarized in Table 12 in order to make it compatible with the other layers for carrying out the multicriteria overlay analysis. The reclassified raster can be seen in Figure 24.

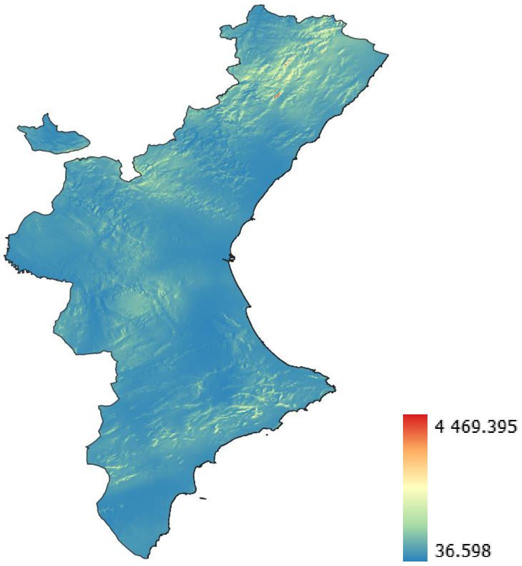

Figure 23. Wind power density raster (W/m²)

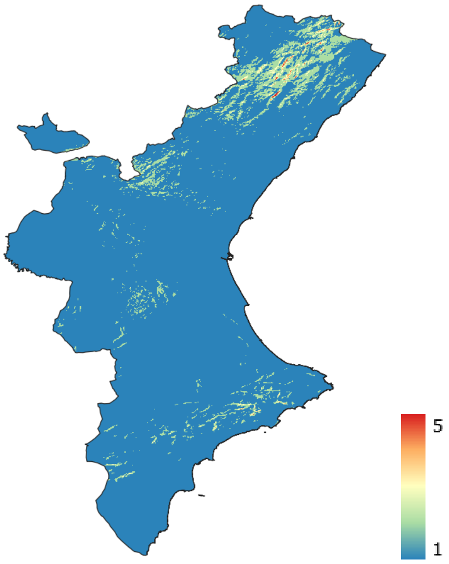

Figure 24. Wind power density reclassified raster

Roads

Regarding hydrogen transportation factors, it is important that the hydrogen production site is close to relevant roads within the geographical boundary. Additionally, when more hydrogen refuelling stations are deployed, it will be interesting that they are built near strategic transportation routes that usually involve federal, primary and secondary roads.

This layer has a relative importance since two enhancing factors are considered: hydrogen transportation and hydrogen consumption. On the one hand, the roads are a feasible way to transport hydrogen from the production point to the consumption location. On the other hand, these roads imply mean potential consumption of hydrogen as a fuel for light and heavy vehicles by the construction of HRS next to them.

Therefore, in order to preprocess the roads layer, georeferenced data from federal, primary and secondary roads has been depicted from the OpenStreetMap [65] and a vector layer of these roads has been created as seen in Figure 25.

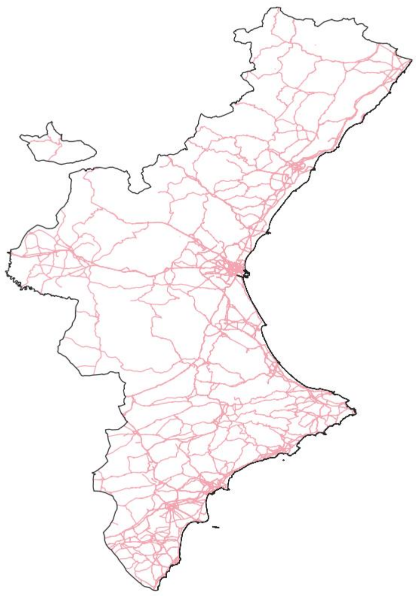

Figure 25. Federal, principal and secondary roads in the Valencian Community vector layer

Then, in order to make it suitable for layer combination, this layer has been rasterized with value 1 pixels for the ones that cover any section of the roads and pixels with value 0 for the rest.

The final step of the roads preprocessing is to create a proximity raster with the QGIS proximity tool's aid that creates a map where each pixel has the value of the distance to the nearest target pixel, being the target pixels those with the value of 1 from the previously rasterized roads layer as represented in

Figure 26.

Since this raster has a wide number of values, for the following overlay analysis it is interesting to reclassify it into six different scores depending on the distance suitability, i.e. from a score of 0 for the sites too close (<0.5km to the roads) and too far (>10km) to a score of 5 for those with a very suitable distance (from 500m to 1km close). In

Figure 27 the most suitable are those in red and the less suitable are the blue areas.

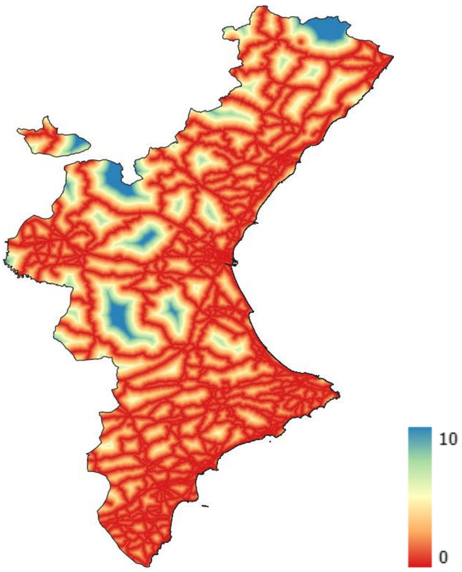

Figure 26. Proximity roads raster (km)

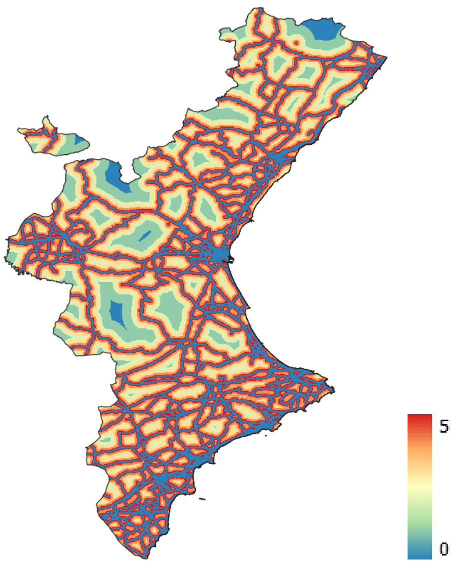

Figure 27. Reclassified roads raster

Railways

Although the railway sector in Spain is widely electrified, with electric trains accounting for 83% of train-km [66], hydrogen transportation remains an intriguing option. This is particularly relevant for the remaining segments of railway lines that continue to rely on fossil fuels, as electrification proves challenging, making hydrogen a promising solution for decarbonizing these sections.

Therefore, a similar approach as in the roads layer is performed in the preprocessing of the railways layer. The railways path of the Valencian Community from the OpenStreetMap [65] have been analysed and represented in Figure 28, creating a vector layer.

Figure 28. Railways of the Valencian Community vector layer

Afterwards, a proximity layer is created following the same methodology as in the roads' proximity layer (see Figure 29) and afterwards, it is reclassified following the same scale as in the roads (see Figure 30).

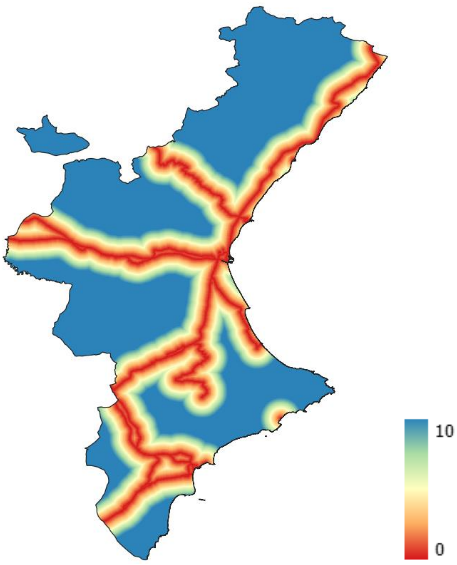

Figure 29. Proximity railways raster (km)

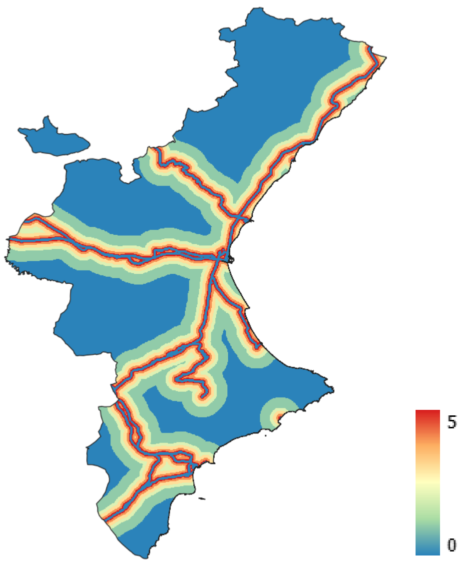

Figure 30. Reclassified railways raster

Airports

Airports can act as a green hydrogen hub whether the hydrogen is used as a fuel for the airplanes or as one energy source for all the facilities within the airport such as HVCA systems, lighting or airport buses.

Thus, all the airports within the Valencian Community are represented in a vector layer extracted from the OpenStreetMap [65] and rasterized afterwards as shown in

Figure 31. Since the aim is to have the production near the demand site, a proximity raster is created and reclassified using the same criteria for the scores. The resulting proximity raster can be seen in

Figure 32.

Figure 31. Airports rasterized layer

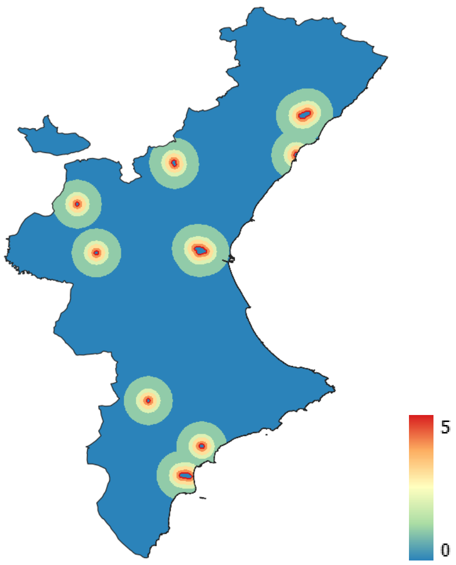

Figure 32. Reclassified proximity airports raster

Seaports

As mentioned in section 6, seaports are a hydrogen demand site for both hydrogen consumption and exportation.

Within the Valencian Community, the key important seaports are the port of Castellón, Sagunto, Valencia, Gandía and Alicante. Thus, a similar approach to the one applied to the airports has been used to generate the proximity layer.

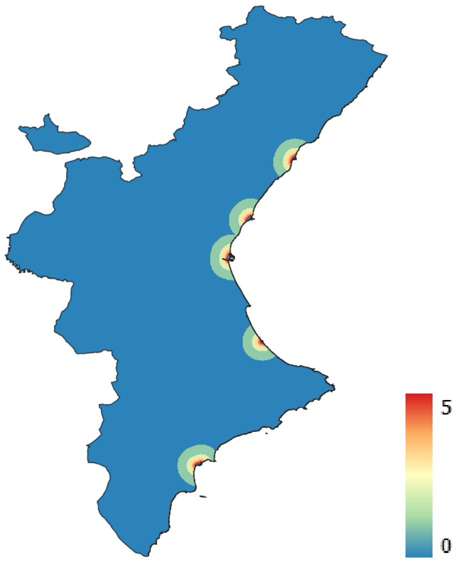

Figure 33. Reclassified seaports proximity layer

Waterbodies

One of the most important layers in this analysis is the one which represents the waterbodies available in the Valencian Community since, as explained before, water is a key input for green hydrogen production.

In the OpenStreetMap there are a lot of different waterbodies represented. They can be classified into rivers, streams, canals, drains, lakes (including dams) and wetlands.

Canals and drains represent waterflows artificially created that already have other uses such as waterpower or irrigation and hence are not considered in this study since the water usage for green hydrogen production should not enter into competition against other key sectors.

Streams differ from rivers because although both are natural waterways, the first one is too narrow that an average person could be able to jump over it. Thus, streams are disregarded in this analysis.

Finally, wetlands are as well disregarded due to several reasons. When there is a natural area which has waterlogged ground or is subject to inundation, it is usually classified as wetland and due to these factors, it has characteristic vegetation. Another reason is that they are usually linked to natural protected area. The most famous within the Valencian Community is "L'Albufera de València".

As a result, it can be seen in Figure 34 that the waterbodies layer will include large enough rives suitable for water extraction and several lakes and dams.

When creating the proximity raster, the coastline will be considered as well due to the possibility to perform a desalination process. After rasterizing the vector layer and calculating the proximity raster, it is reclassified following the scores stated in Table 12 where the lowest scores belong to the sites too close to waterbodies (<500m) and too far (>10km) and the highest are set to the sites close enough and decrease gradually until reaching 10km.

Figure 34. Waterbodies raster

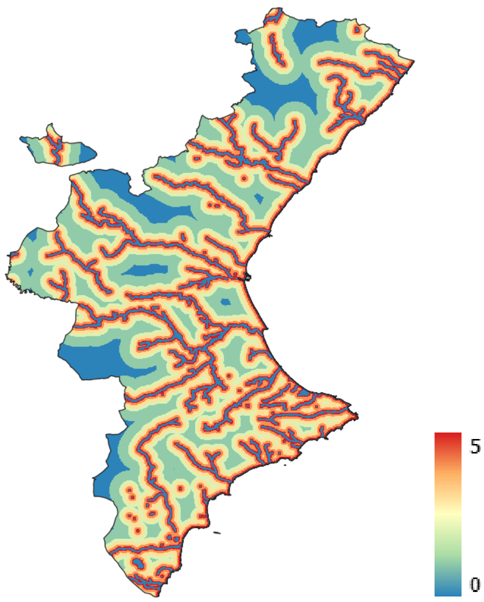

Figure 35. Reclassified proximity waterbodies raster

Additionally, desalination plants in the Valencian Community are not working at their full capacity and they could be a source of purified water for the electrolysis process. Therefore, in order to complete this layer the proximity to these desalination plants will be added.

The main desalination plants in the Valencian Community are listed in Table 10.

Table 10. Desalination plants capacity in the Valencian Community

Desalination plant	Capacity
Oropesa	17.79 [67]
Moncofar	10.95 [67]
Sagunto	8.36 [67]
Mutxamel	18.25 [67]
Alicante I	21 [68]
Alicante II	23.7 [68]
Torrevieja	80 [69]

Once they have been located, the same procedure as for the ports has been performed in order to obtain the proximity desalination plants proximity raster. However, in this case the scale has been set as show in Table 11.

Table 11. Suitability scores for desalination plants

Proximity to desalination plant (km)	Score
< 0.5	5
0.5 – 1	4
1 – 2.5	3
2.5 – 5	2
5 – 10	1
> 10	0

The resulting layer by applying the previous scale can be seen in Figure 36.

In order to add this layer to the overall waterbodies layer, a simple weighted overlay analysis is performed with the proximity to desalination plants having a 0.2 weight and the other waterbodies a weight of 0.8. The resulting layer can be seen in Figure 37.

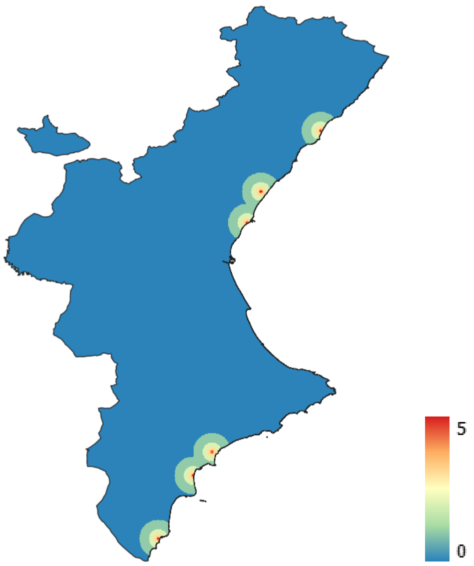

Figure 36. Reclassified proximity to desalination plants layer

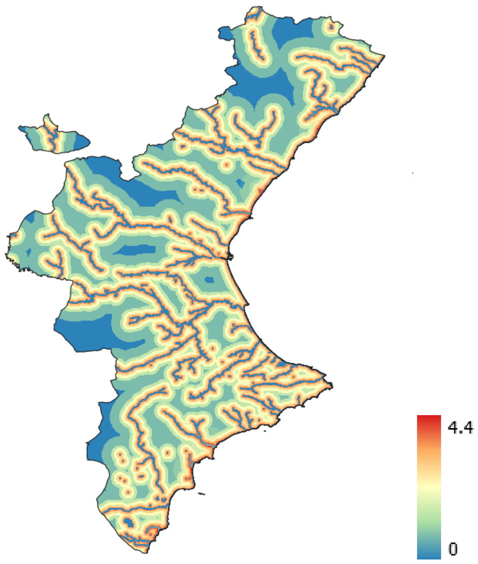

Figure 37. Reclassified proximity overall waterbodies raster

Major urban centres

The energy demand in the major urban centres will play a key role in driving the green hydrogen industry. This demand stems from various sectors, including residential and commercial establishments as well as public and private transportation.

Therefore, the layer with the major urban centres of the Valencian Community has been created, considering the cities with a population greater than 100000, as shown in Figure 38.

A similar approach as the proximity criteria for the airports has been applied to the major urban centres. However, it has been considered that a bigger distance from the city centre (than the distance from the airport centre) is still suitable since the demand can be distributed through all the municipal territory. Thus, the scores for the proximity in this case ranges from 0 for the sites further than 30km to 5 for the sites closer than 5km resulting in Figure 39.

Figure 38. Major urban centres in the Valencian Community

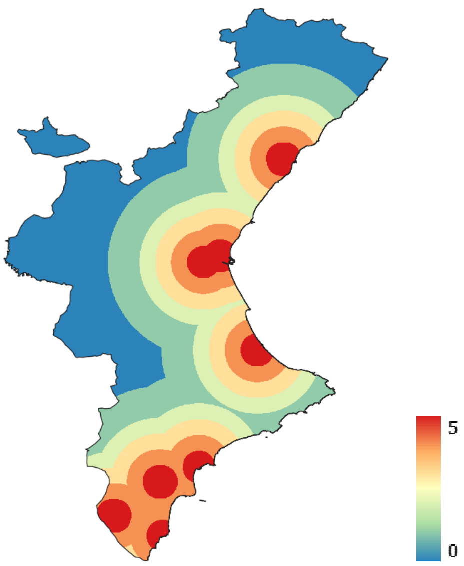

Figure 39. Reclassified major urban centres layer

Industrial demand sites

Apart from the potential consumption of hydrogen in the transport sector and in strategic sites such as seaports and airports, there are several industries where hydrogen is currently consumed and some, where green hydrogen can help with the decarbonization of their energy intensive processes.

As stated in section 5, in the Valencian Community there is a wide range of companies within those sectors and in order to develop a layer to include this information in the analysis, the industrial parks or industrial areas where these companies are established have been represented as can be seen in the figure below. Specifically, in Figure 40 the ceramic cluster in Castellón is represented together with some fertilizer companies in Sagunto and Silla, and the refinery and the chemical plant in Castellón.

After the industrial demand analysis, the proximity raster is obtained classifying the sites following the scale set in Table 12.

Figure 40. Industrial demand vector layer

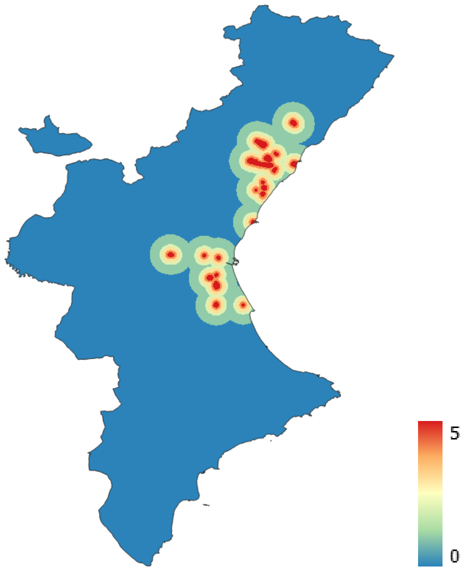

Figure 41. Industrial demand proximity reclassified raster

Power lines

While an integrated green hydrogen facility typically involves the co-location of a solar PV plant or a wind farm with an electrolyzer, an alternative approach is to procure green electricity from the national grid via Power Purchase Agreements (PPAs) with renewable power generation plants. Another possibility is to harness surplus renewable electricity from other regions.

It is important to note that only power lines with a voltage over 110kV have been located for this layer since the other existing lines are low voltage lines that are not designed to transport electricity for large distances and are mainly aimed for electricity distribution.

Using Figure 42 as the base layer, a proximity raster layer for the power lines has been created which has been afterwards reclassified as one can see in Figure 43. For the scoring classification it has been considered that lines further than 10 km do not give any advantage since the costs of installing a power line longer than 10 kilometres will have a significant impact in the hydrogen production facility.

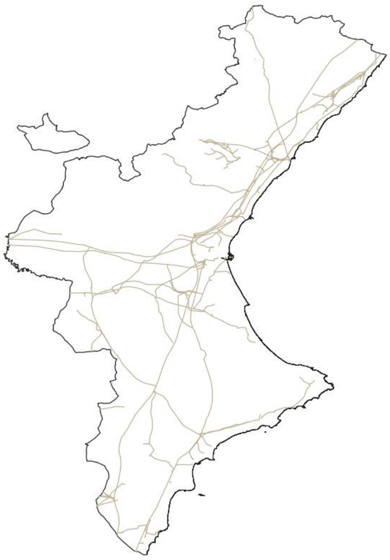

Figure 42. Power lines >110kV in the Valencian Community

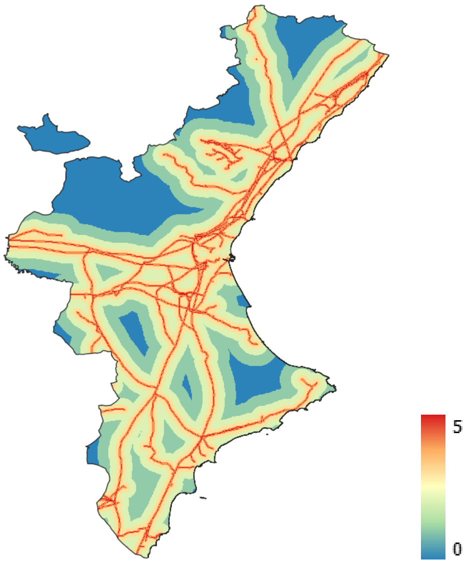

Figure 43. Power lines proximity reclassified raster

Natural protected areas

As one could easily conclude, hydrogen production facility should be far from any type of natural protected area. Thus, the most suitable sites are those that are further from the protected areas.

For this layer, natural protected areas have been extracted from the OpenStreetMap [65] as one can see in Figure 44. Contrary to the other proximity layers, in this case the low score values will be assigned to the sites that are close to the target pixels, i.e. the natural protected areas as seen in Figure 45 where the natural protected areas and their surroundings are in a lighter colours and the sites further than 10 km have the higher score.

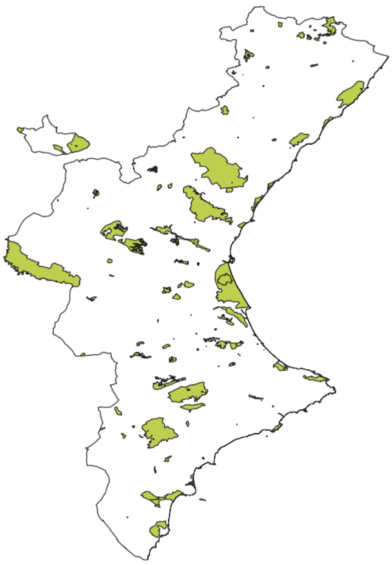

Figure 44. Natural protected areas layer in the Valencian Community

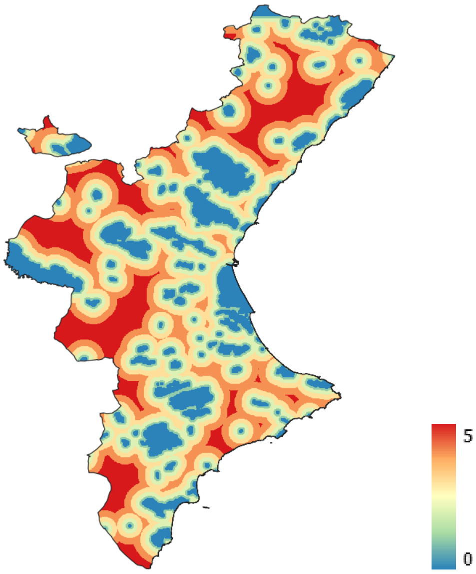

Figure 45. Natural protected areas proximity reclassified raster

Table 12. Suitability scores for the criteria

Score	GHI (yearly kWh/m²)	Wind power density (W/m²)	Proximity to roads (km)	Proximity to railways (km)	Proximity to airports (km)	Proximity to ports (km)	Proximity to waterbodies (km)	Proximity to major urban centres (km)	Proximity to industrial demand sites (km)	Distance to natural protected areas (km)	Proximity to power lines (km)
5	>1675.85	>2904.77	0.5-1	0.5-1	0.5-1	0.5-1	0.5-1	<5	<1	>10	<0.1
4	1534.57-1675.85	2185.15-2904.77	1-2	1-2	1-2	1-2	1-2	5-10	1-2	10-6.5	0.1-0.5
3	1393.29-1534.57	1465.53-2185.15	2-3.5	2-3.5	2-3.5	2-3.5	2-3.5	10-15	2-3.5	6.5-4	0.5-2
2	1252.01-1393.29	745.91-1463.53	3.5-5	3.5-5	3.5-5	3.5-5	3.5-5	15-20	3.5-5	4-2	2-5
1	1110.73-1252.01	26.29-745.91	5-10	5-10	5-10	5-10	5-10	20-30	5-10	2-1	5-10
0	<1110.73	<26.29	<0.5 and >10	<0.5 and >10	<0.5 and >10	<0.5 and >10	<0.5 and >10	>30	>10	<1	>10

Layers' weighted overlay

Once all the layers have been pre-processed, it is time to apply the weights calculated in the previous step and summarized in Table 8. Thus, performing the multi-criteria weighted overlay analysis in QGIS, the output layer can be seen in Figure 46, where the most suitable sites are coloured in red with decreasing levels of suitability depicted by a spectral colour ramp.

The equation (9) is applied to calculate the suitability raster:

0.1943 * "Reclassified_GHI_CV@1" + 0.1943 * "Reclassified_PowerDensity100m_CV@1" + 0.0702 * "Reclassified_Roads@1" + 0.0269 * "Reclassified_Railways@1" + 0.0828 * "Reclassified_Seaports@1" + 0.0217 * "Reclassified_Airports@1" + 0.2343 * "Reclassified_overall_waterbodies@1" + 0.0228 * "Reclassified_MajorUrbanCenters@1" + 0.0141 * "Reclassified_PowerLines@1" + 0.0674 * "Reclassified_IndustrialDemand@1" + 0.0711 * "Reclassified_ProtectedAreas@1" (9)

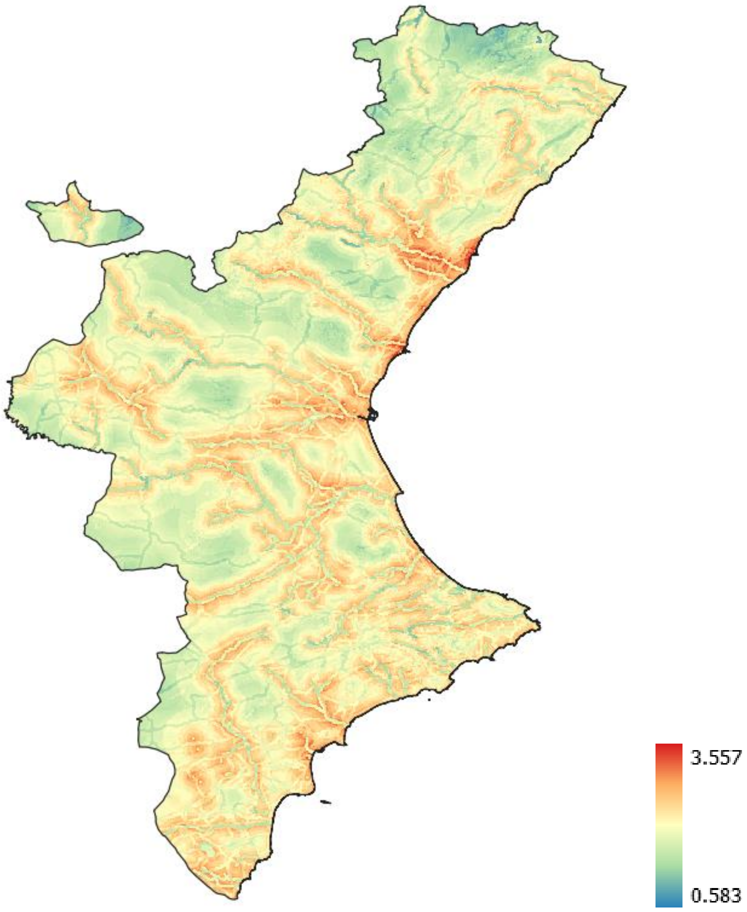

Figure 46. Suitability map

Although several criteria have been applied while performing the Multi-Criteria Weighted Overlay Analysis (MCWOA), it is necessary to include some layers that should be excluded from the suitable areas at all such as residential areas, protected areas. Thus, after overlaying these layers the following map is obtained where the protected areas and buildings are represented in black areas which are excluded from the possible suitable area no matter the score those sites obtain.

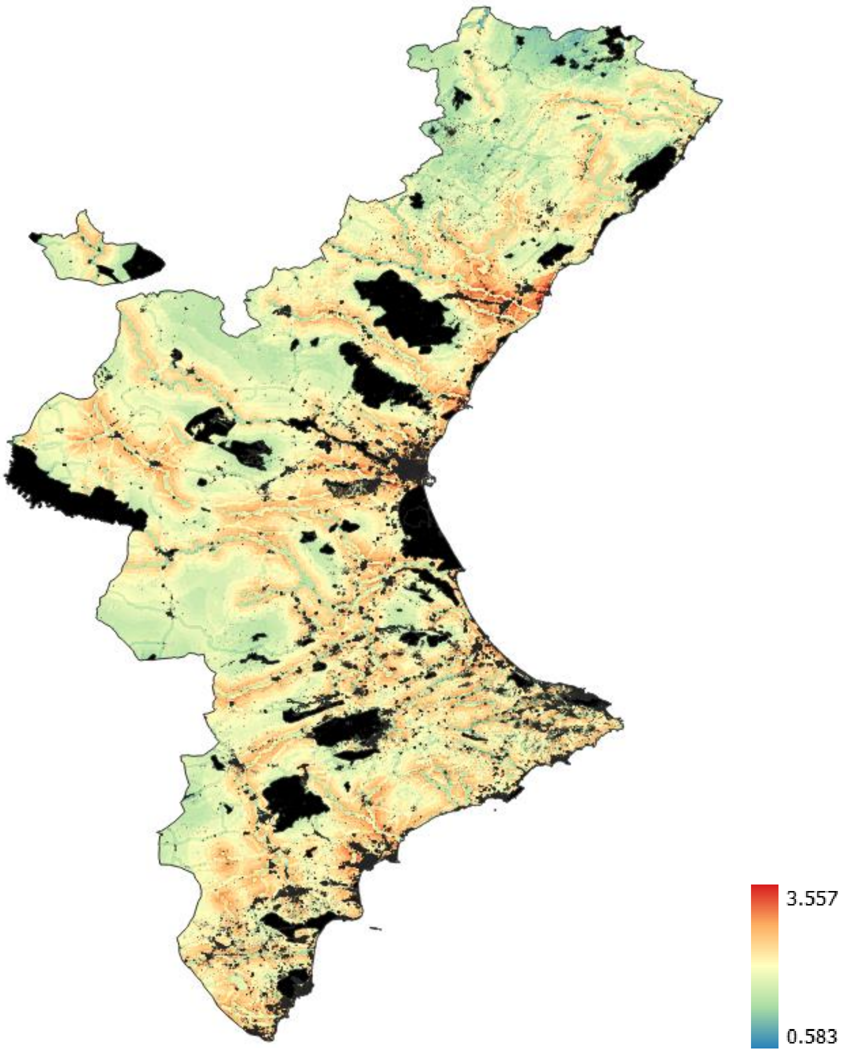

Figure 47. Suitability map with buildings and protected areas

3.4.3 Suitable locations

Location 1

As one can see in the resulting map (Figure 46), the area with the highest score (3.557) and hence deemed as the most suitable area for a green hydrogen production facility is the one in the north of the Valencian Community. More specifically, this area is next to the port of Castellón around the ETRS89 / UTM zone 30S X: 756011.00, Y: 4427590.00.

After identifying the most suitable area based on the selected criteria, it is important to explore it in a satellite view and have a better understanding of its surroundings. Specifically in this case, the pixel with the highest score coincides with the ubication of the Combined Cycle Power Plant of Castellón as seen in the below image (Figure 48).

Figure 48. Satellite suitable area 1

It is important to note that the surrounding pixels would have similar scores and hence they are still suitable for green hydrogen production and share the advantages of their neighbouring top score pixel. In the raster represented in Figure 49 one can identify in black the roads (CS-22 and N-225) on the north-west delimiting the most suitable area and the Mijares river in blue limiting the suitable area on the south together with the Mediterranean Sea at the east.

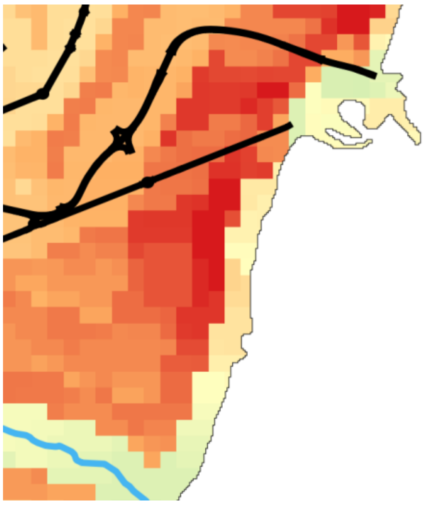

Figure 49. Raster suitable area 1

Analysing the satellite image and the raster scores, it is clear that the most suitable area will be any of the available land which surrounds the industrial area and limited by the roads, the Mijares river and the Mediterranean Sea (bottom-right of the figure).

Location 2

Another site in the province of Valencia with totally different characteristics due to its relatively inland location but still with a great suitability score (3.26) is located around the metropolitan area of the city of Valencia. Specifically, the area with this is score is between the towns of Paiporta and Picanya ETRS89 / UTM zone 30S X: 721362, Y: 4367613.

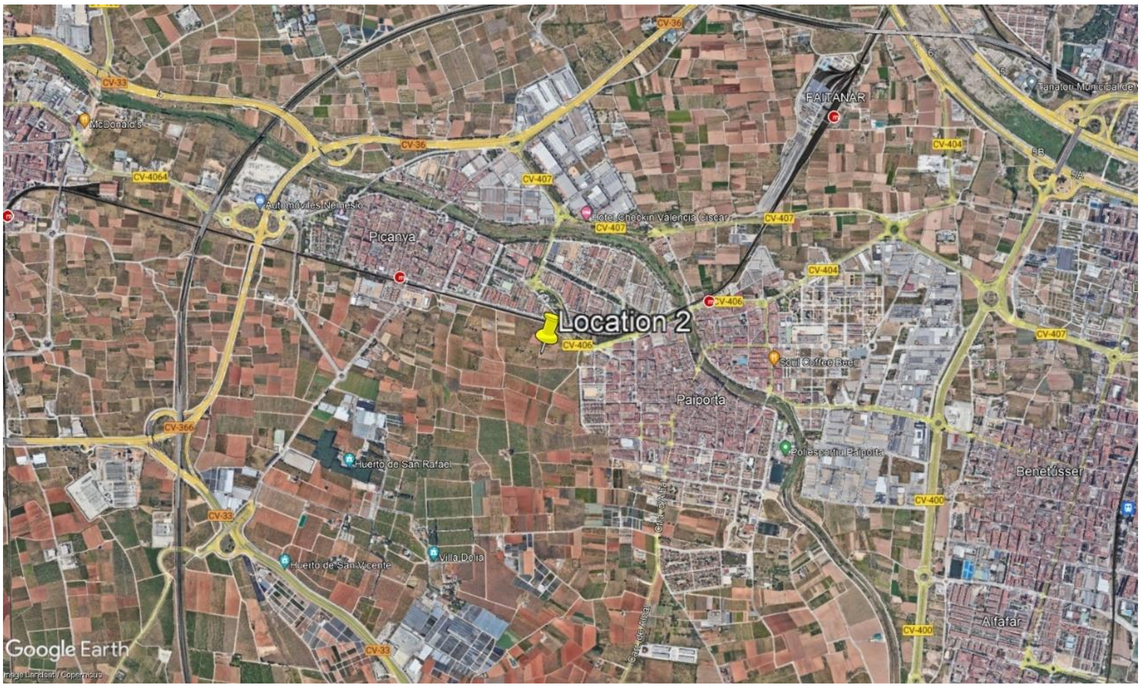

Figure 50. Satellite suitable area 2

As one can see in Figure 50, the suitability of this site is enhanced by the surrounding primary and secondary roads such as the CV-33, CV-36 and CV-407, as well as its proximity to the major city centres of Torrent and Valencia or the nearby chemical industry of Valencia. Additionally, proximity of the airport of Valencia and the Turia river to this location contributed to its high suitability score.

Location 3

Finally, another spot highly ranked in the suitability map is an area at the south of Alicante with a score of 3.4. A distinctive advantage of this site is that it is less than 2 km away from the desalination plants of Alicante. This makes it especially suitable for an area in the Valencian Community where rainfall is not likely to happen and the only excess water for electrolysis could come from there.

As one can see in the following image, the third analysed suitable area is located in ETRS89 / UTM zone 30S X: 716059, Y: 4242744.

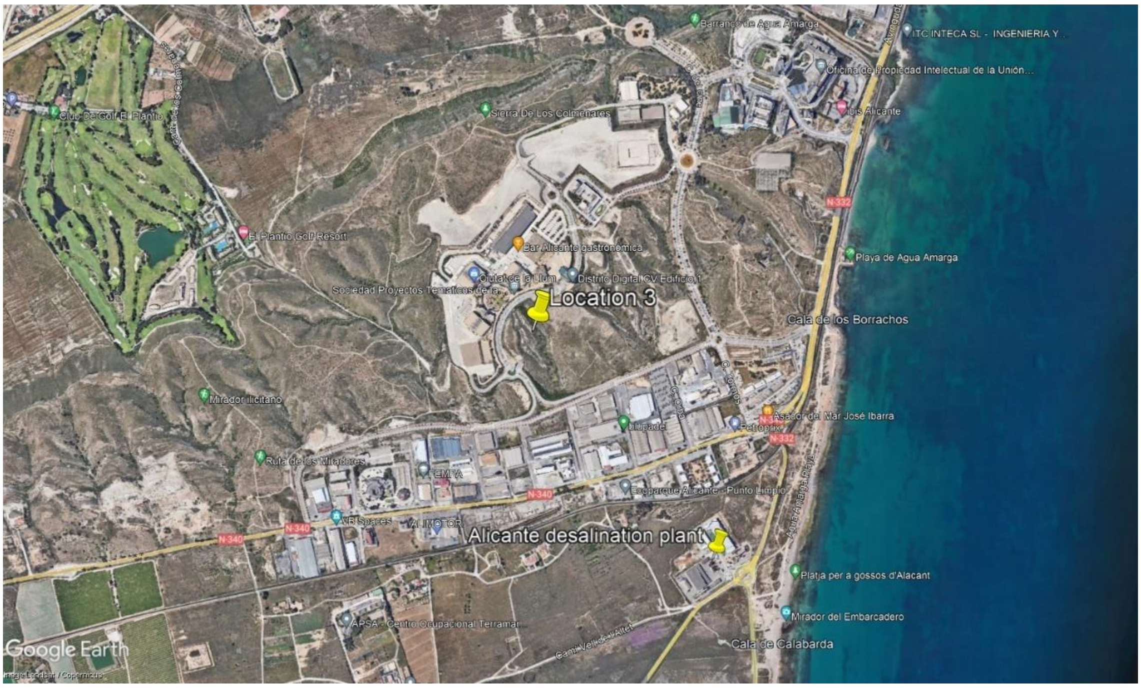

Figure 51. Satellite suitable area 3

The fact that the green hydrogen production facility is not next to the desalination plant is because there is a natural protected area next to it, the "Saladar d'aigua Amarga" which additionally is a floodable zone, not a suitable terrain for an installation like this at all.

3.5 Calculations

Once the suitable area is identified, calculations about water availability, energy requirements, land availability and renewable power installation must be performed in order to obtain the potential green hydrogen production.

3.5.1 Water availability

Water resources in Spain are regulated through organizations called "Confederaciones Hidrográficas" which cover the territory of a big river basin or a territory which shares several linked smaller river basins. The last of the before mentioned is the case of the Valencian Community which belongs to the "Confederación Hidrográfica del Júcar". This distribution can be seen in the following map (see Figure 52).

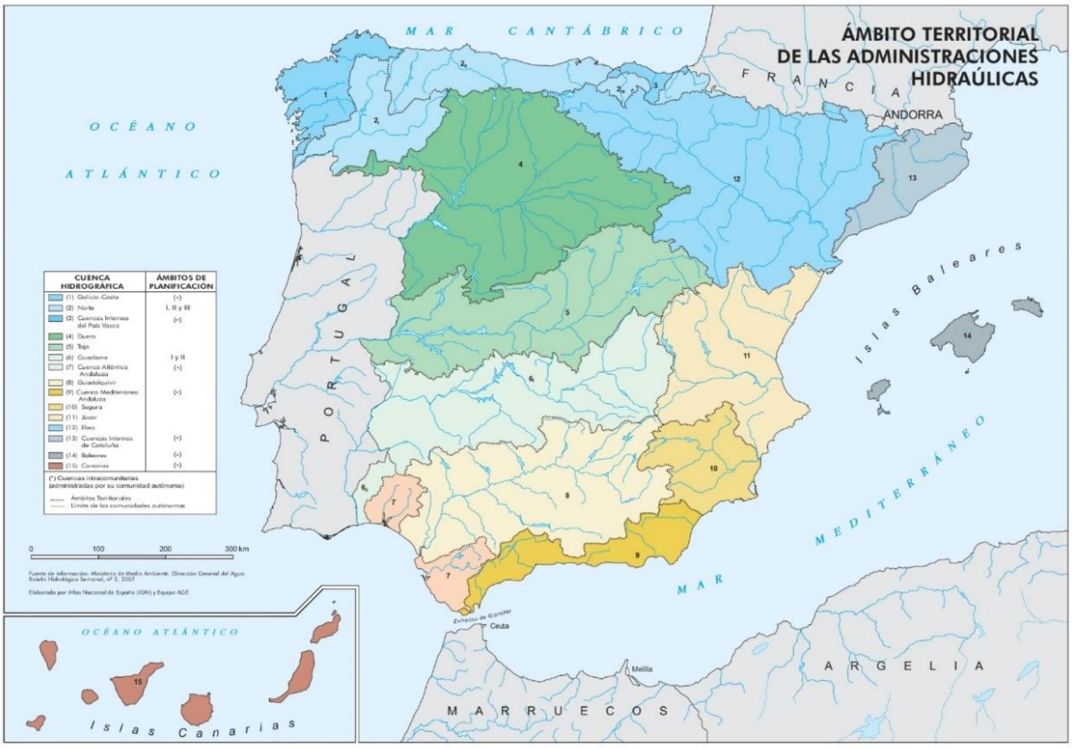

Figure 52. Spanish "Confederaciones Hidrográficas" map [70]

Additionally, river basins can be further divided into "sistemas de explotación" which could be translated as "water resources management systems" in which the municipalities belonging to them can make use of the water available in that region. This subdivision can be seen in the following map.

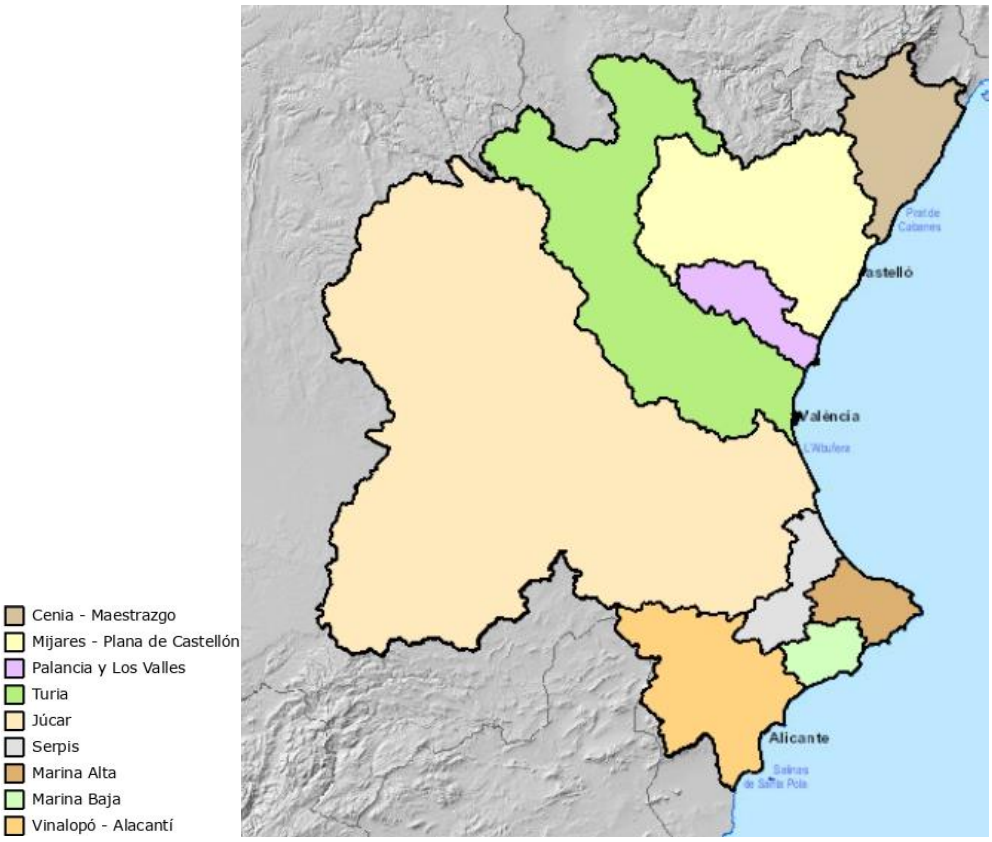

Figure 53. Water resources management systems of the Confederación Hidrográfica del Júcar [71]

And as one can identify, the most suitable areas for the green hydrogen production are distributed in the Mijares-Plana de Castellón system for the location 1, the location 2 is in the Turia system and the location 3 in the Vinalopó - Alacantí. Thus, the water availability of these areas will be assessed.

Mijares – Plana de Castellón

In order to assess water availability in the different water resources management systems the "Plan Hidrográfico del Júcar" [67] has been used since in this document there is a study of water resources and water demand planification from 2022 to 2027 of the whole Confederación Hidrográfica del Júcar.

The Mijares-Plana de Castellón system, shown in Figure 54 includes all the river basins of Mijares, Seco, Veo, and Belcaire, as well as all of the coastal sub-basins between Benicasim, including its municipal area, and the provincial border between Castellón and Valencia. It originates in the Gúdar Mountains in the province of Teruel and flows into the sea between the towns of Almazora and Burriana in the province of Castellón. Its main tributaries include the Valbona, Villahermosa, and Rambla de la Viuda rivers on the right bank and the Albentosa and Montán rivers on the left. The total area covered by this exploitation system is 4818 km² [67].

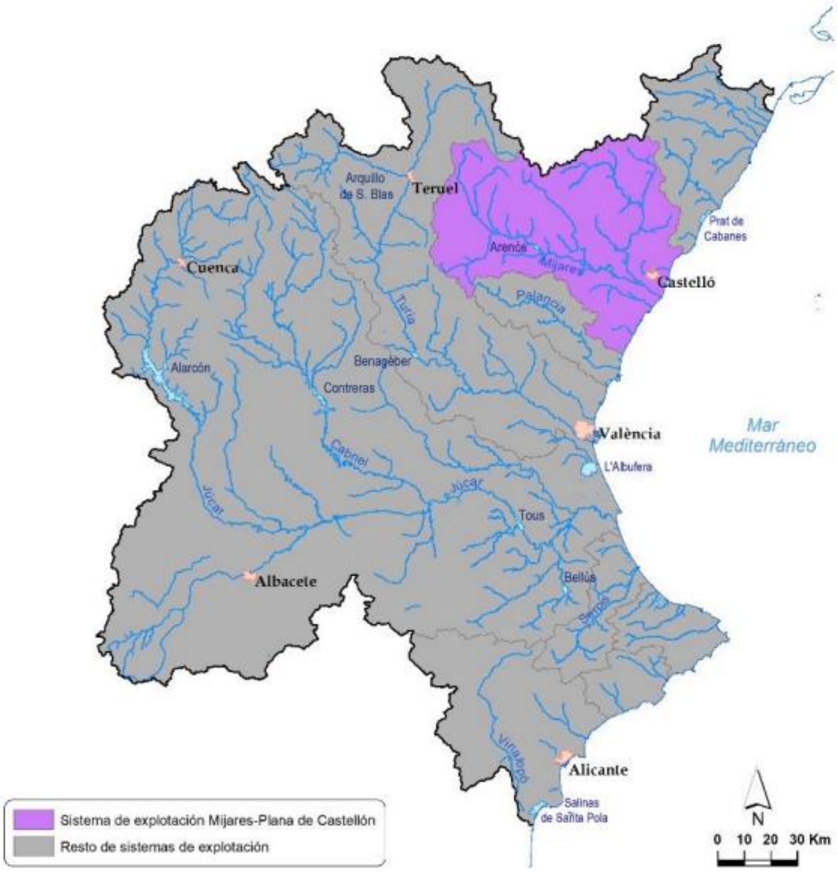

Figure 54. Mijares - Plana de Castellón system [67]

Water resources in each system can be divided into four different categories depending on the source as surface water, groundwater, water treatment plants and desalination plants.

Regarding the groundwater, in [67] it is stated that there are several groundwater bodies in the Mijares-Castellón de la Plana system that are being pumped in order to meet the water demand of the covered area. Those are Javalambre Oriental, Mosqueruela, Lucena – L'alcora, Onda - Espadán, Plana de Castelló, Azuébar - Vall d'Uixó and Maestrazgo Oriental.

The other sources of water are the water treatment plants and water desalination plants. There are several water treatment plants in the different municipalities of the system: Almazora, La Vall d'Uixó, Castellón de la Plana, Onda-Bechi-Vilareal-Alquerias, Burriana, Benicasim and Moncofa.

However, regarding sea water treatment in desalination plants in the Mijares-Plana de Castellón system there is only one desalination plant in Moncofa which has a capacity of 10.9 hm^3/year but currently it is at a level of 1.18 hm^3/year due to the O&M costs.

Adding all the water sources, there are 258.29 hm^3/year available in the system to be used to meet the water demand of the area.

When it comes to the water demand, according to [67] the Mijares-Plana de Castellón system demanded 243.32 hm^3 during the year 2018 being the third system with the highest demand which can be divided into four types as seen in Figure 55.

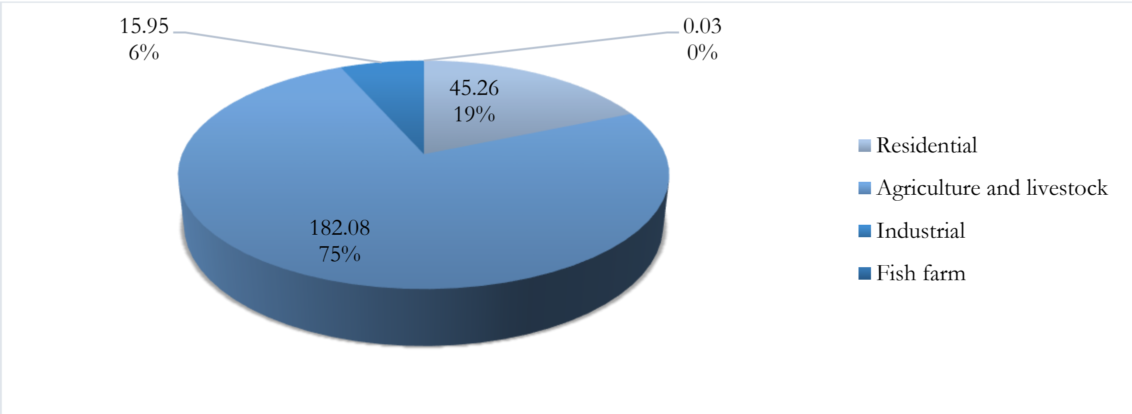

Figure 55. Water demand per sector. Mijares - Plana de Castellón [67]

Additionally, [67] studied from where the water comes to supply this demand depending on whether it is surface water, groundwater, treated wastewater or desalinated water (see Figure 56).

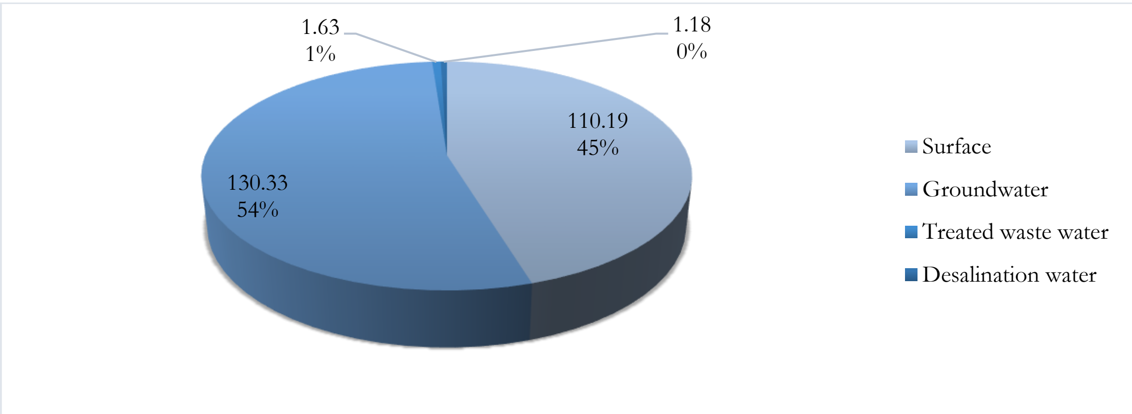

Figure 56. Source used to meet the water demand. Mijares - Plana de Castellón [67]

The final step to obtain the water availability for green hydrogen production is to calculate the difference between the water available in the resources minus the water demand.

$$AW_{GHP} = AW_{WR} - WD = 258.29 - 243.32 = 14.97\ hm^3/year \qquad (10)$$

However, it is important to note that the groundwater in this system has a pumping rate greater than the available water source [67] and hence the water available for electrolysis must come from surface resources or desalination plants.

Turia

The two main water resources management systems in the province of Valencia and in the Júcar River Basin Demarcation are the Jucar system, demanding more than half of the water demand of the Demarcation and the Turia being the second one. In this case, the location 2 belongs to the Turia system.

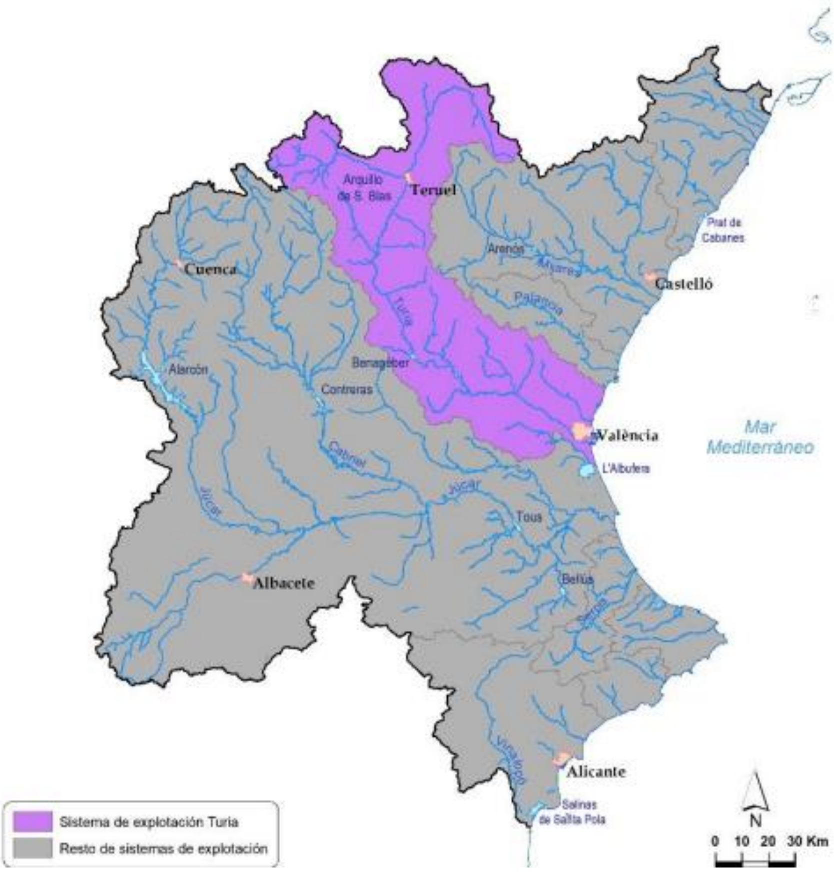

Figure 57. Turia system [67]

The Turia system in Figure 57 above, encompasses the basin of the Turia River, as well as those of the Carraixet and Poyo ravines, and the coastal sub-basins located between the northern boundary of the municipality of Puçol and the El Saler inlet. The Turia River, which originates in the muela de San Juan in the province of Teruel, is also known as Guadalaviar until it meets with the Alfambra River. Its main left-bank tributaries are the Camarena, Riodeva, Arcos, and Tuéjar rivers, while on the right bank it is joined by the Ebrón, Vallanca, and Sot rivers. In total, the system covers an area of 7240 km² [67].

The total water available in the own resources of the system plus the one which is possible to obtain reutilize through wastewater treatment plants is 498.24 hm³/year.

Regarding the water demand, as stated before it is the second most consuming water resources management system with 583.24 hm³/year of water divided as seen in Figure 58 and Figure 59.

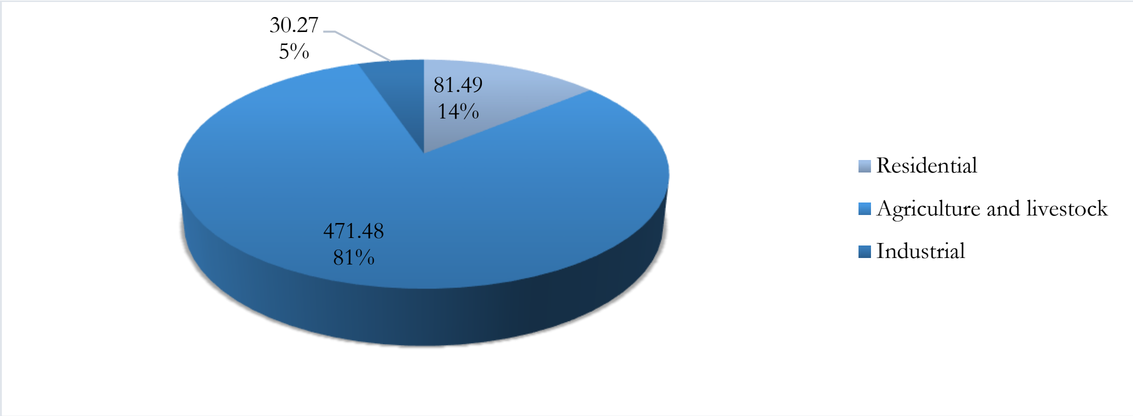

Figure 58. Water demand per sector. Turia [67]

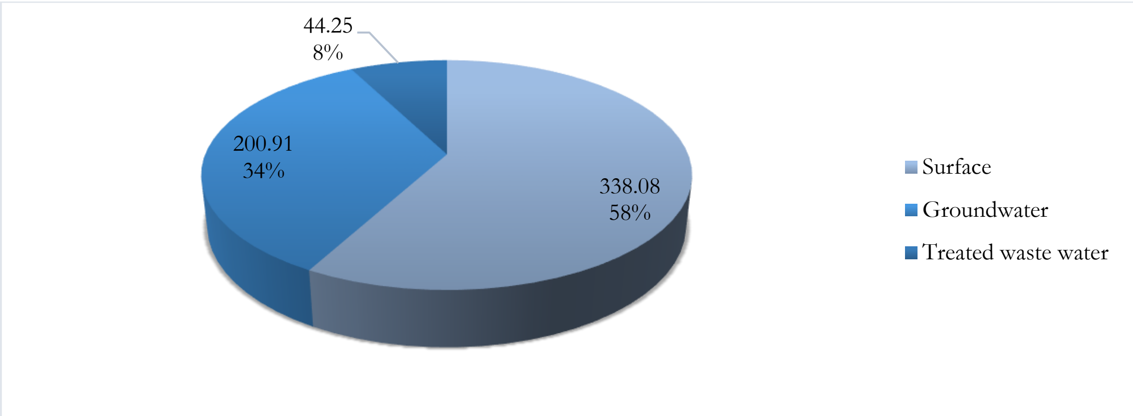

Figure 59. Source used to meet the water demand. Turia [67]

As one could expect, seeing that the water demand is much higher than the own resources plus the reutilized water, the balance of water availability results negative.

$$AW_{GHP} = AW_{WR} - WD = 498.24 - 583.24 = -85\ hm^3/year \qquad (11)$$

This means that both surface and groundwater are exploited at higher levels than they can be recovered and thus, the only possibility to obtain water for a hydrogen facility without entering in a competition with other sectors is to perform a desalination process to water from the Mediterranean Sea.

Vinalopó – Alicantí

The last location belongs to the further south area of the Demarcation, the Vinalopó – Alacantí water resources management system. This system, as shown in Figure 60 includes the basins of the Vinalopó and Montnegre rivers, the Rambuchar ravine, and the coastal sub-basins between the northern boundary of the municipality of Campello and the southern boundary of the hydrographic demarcation. The total area of the system is 2984 km², spanning across the provinces of Albacete, Alicante, Murcia, and Valencia. To the west, it borders the Segura hydrographic demarcation, while to the north it borders the systems of Júcar, Serpis, and Marina Baja.

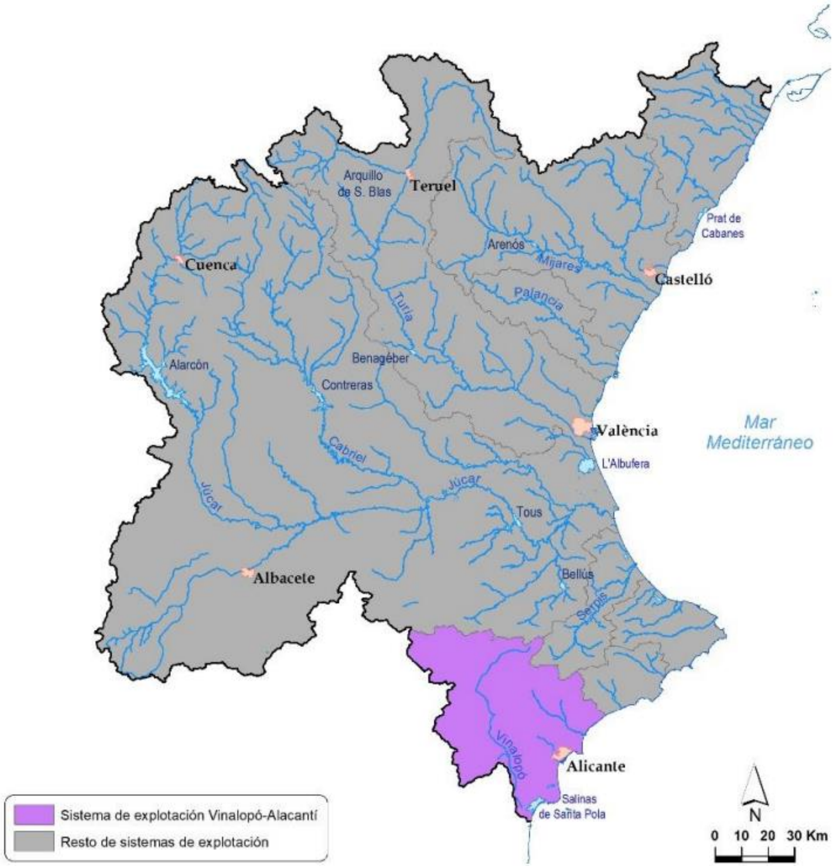

Figure 60. Vinalopó - Alacantí system [67]

As one can see, its main source of water availability is not as differentiated as in the other systems due to its rainfall scarcity. Thus, wastewater treatment plants and desalination plants play a key role in this system. Summing all the stated water resources, one can conclude that there are 137.63 hm^3/year available to meet the system demands.

Although its resources place the Vinalopó – Alacantí system among the three system with the lowest water resources, its demand does not match this ranking being right after the Mijares – Castellón de la Plana system 172.11 hm^3/year demand of water. This demand is shared among the sectors shown in Figure 61.

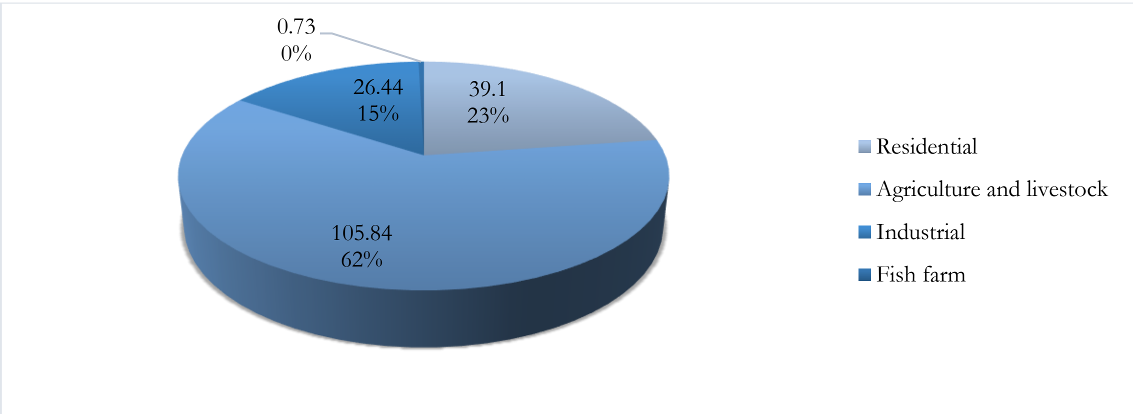

Figure 61. Water demand per sector. Vinalopó – Alacantí [67]

And met by the different sources as shown in Figure 62.

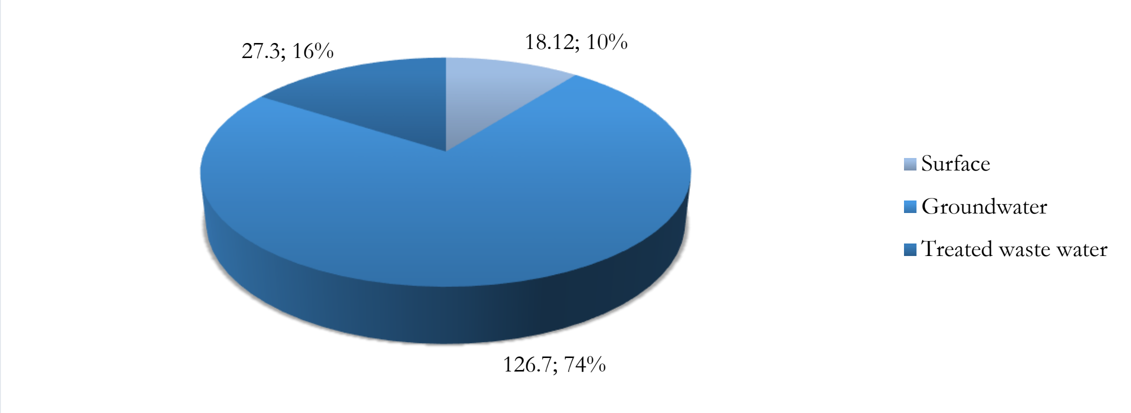

Figure 62. Source used to meet the water demand. Vinalopó – Alacantí [67]

$$AW_{GHP} = AW_{WR} - WD = 137.63 - 172.11 = -34.48\ hm^3/year \qquad (12)$$

The resulting water availability balance is negative. However, in the study performed in [67] from where all the data come from, the desalination plants Alicante I and Alicante II which are next to the suitable location are not considered.

Those have a capacity of 21 and 23.7 hm^3/year respectively and hence if we add these two to the previous performed balance it would result in 10.22 hm^3/year overall water availability for the green hydrogen production in the Vinalopó – Alacantí system which of course must come from those desalination facilities.

3.5.2 Standardized 1 MW electrolyzer facility

In this section, a 1MW electrolyzer facility is going to be assessed in order to make the installations in different sites comparable among them.

Due to its level of standarization and data availability, the electrolyzer selected for this case study is the PEM electrolyzer EL200N from the Spanish company H2B2 whose main parameters can be seen in Table 13.

Table 13. H2B2 electrolyzer main characteristics

Electrolysis type	PEM
Max. nominal hydrogen flow	200 Nm^3/h (430 kg/day)
Operating pressure	15 – 40 bar
Power consumption (BoP + Stack)	5.1 kWh/Nm^3 H_2
Demi water consumption	< 1 L/Nm^3 H_2

Electricity generation

Primarily, since the suitable areas do not coincide with the areas with the most wind density in the Valencian Community (see Figure 63), it has been disregarded the possibility to obtain renewable electricity through wind power and hence only solar PV electricity generation will be considered.

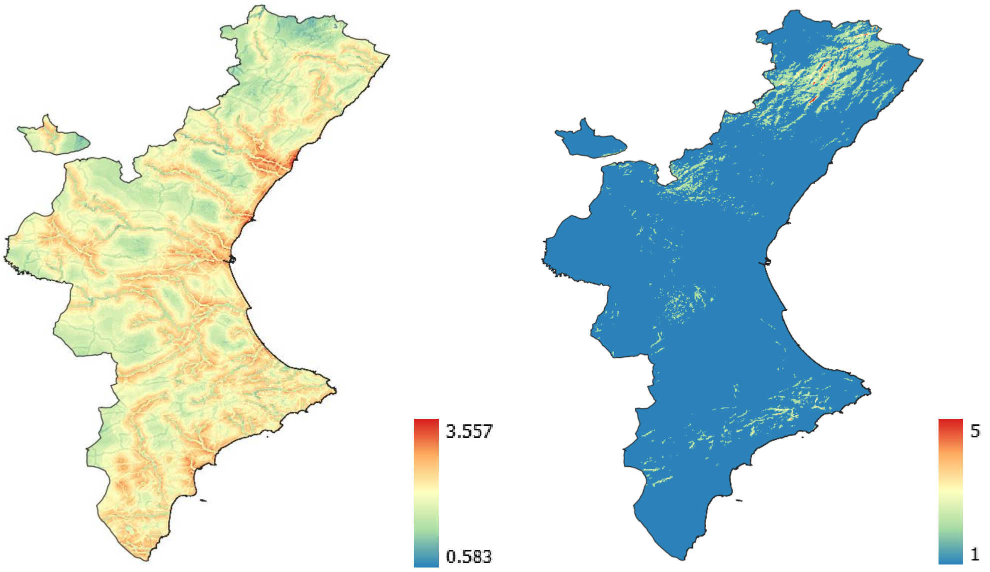

Figure 63. Suitability vs wind power density map

In order to determine the size of the solar PV plant associated to the 1MW electrolyser, a pareto front analysis has been conducted as presented in Figure 65 and Figure 66

With the aid of the software Solargis, the hourly average PV electricity production of a solar PV installation with a tracker standard configuration of different peak power from 1MWp to 3MWp has been simulated. As one can see in Figure 64, the electrolyzer maximum capacity of electricity consumption is limited to its 1MW power which means that there will be some curtailment during the central hours of the day if the PV installation is greater than 1MW. However, this would only happen with perfect sunlight conditions.

Therefore, since the electrolyzer is the most expensive component of the installation, in this analysis the goal was to find a compromise solution where the electrolyzer is working the maximum hours of the day while not increasing the size (cost) of the PV installation without a great increment of these working hours.

In Figure 64 one can see that a PV installation of 2.33 MWp could be a proper sizing since the working hours of the electrolyzer are much greater than the 2MWp case and only a few hours less than the 2.66 MWp case (saving the cost that involves increasing the PV peak power). However, a deeper analysis of this casuistry is done in Figure 65 and Figure 66.

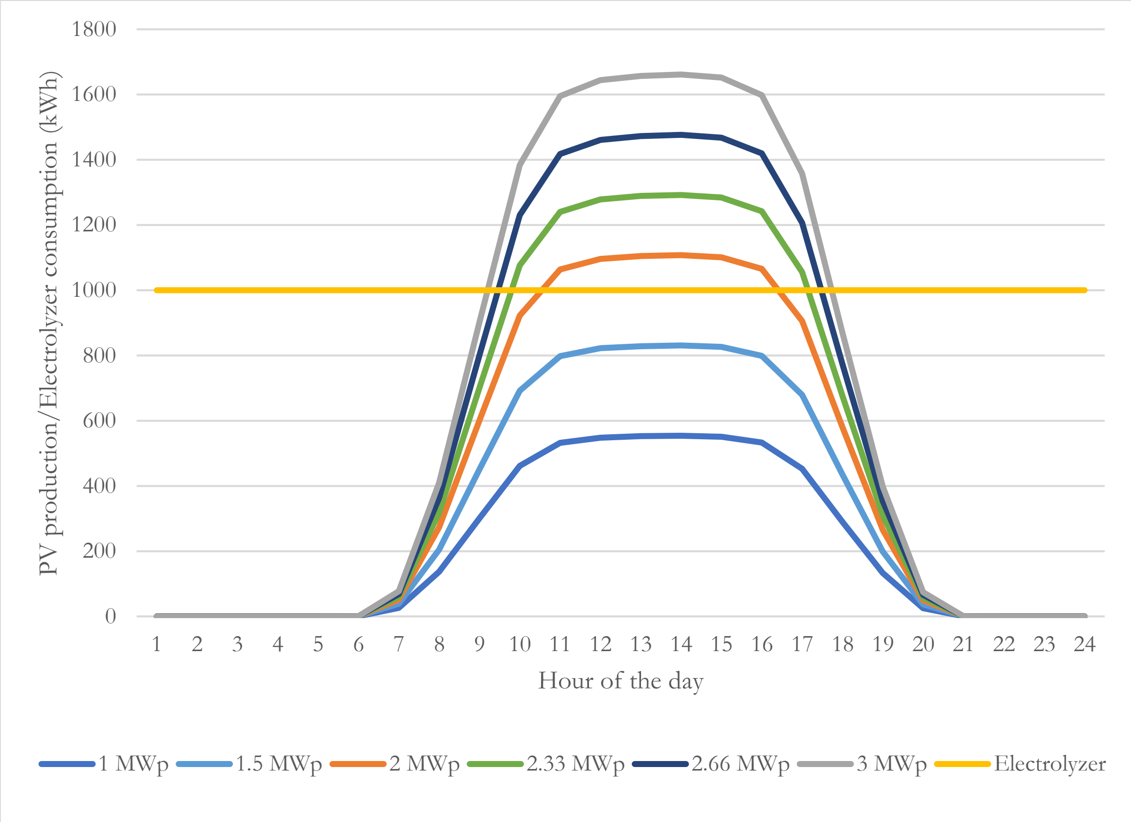

Figure 64. Hourly average PV electricity production vs Electrolyzer max. consumption

In order to decide the most technically and economically efficient solar PV capacity two graphs have been performed. In Figure 65 one can see the curtailment vs the cost of the PV installation and in Figure 66 the actual electricity used by the electrolyzer considering the curtailment for the different configurations.

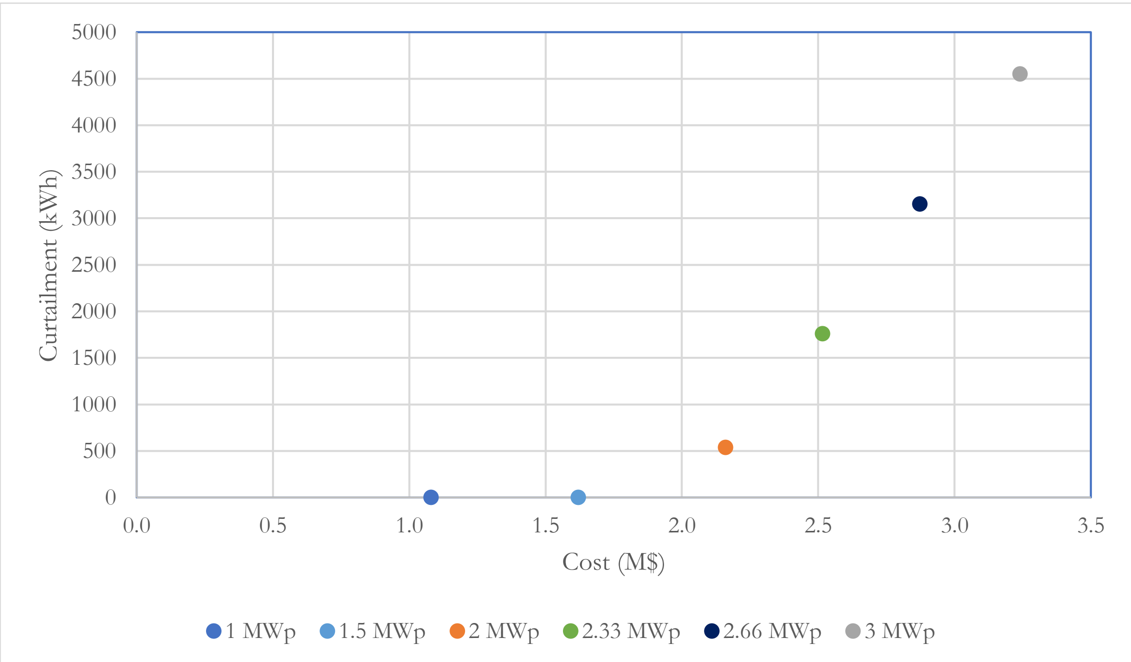

Figure 65. Curtailment vs Cost

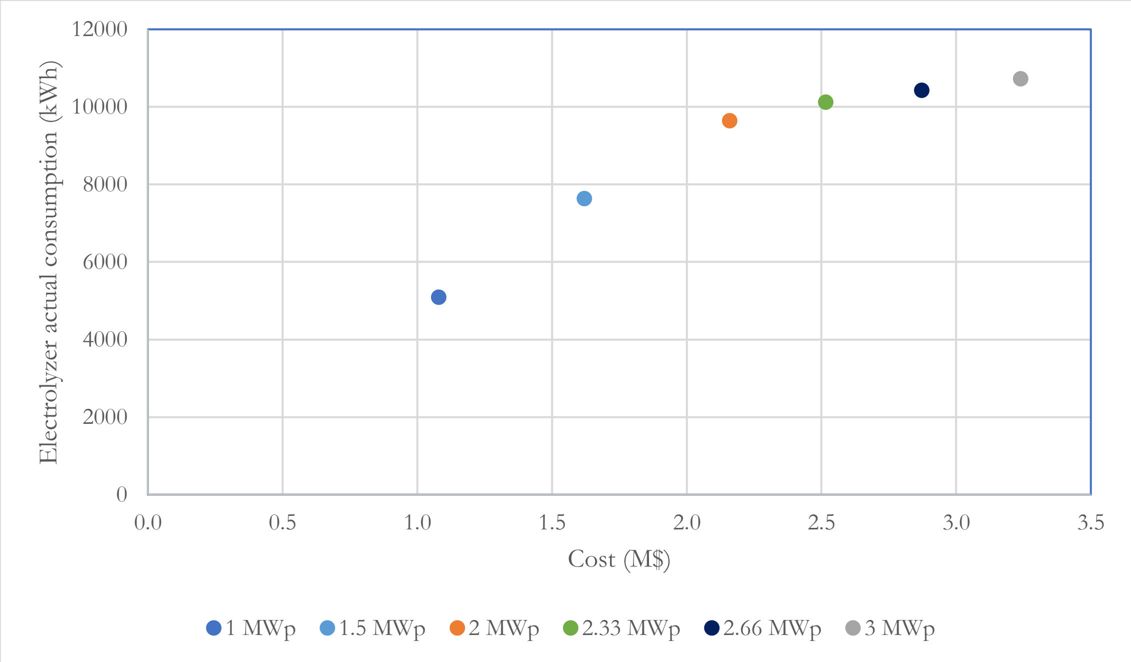

Figure 66. Electrolyzer electricity consumption vs Cost

Analyzing both graphs, it seems efficient to select a configuration before the trend lines behave exponential. This is, before the cost (in Figure 66) starts increasing without having a significant impact in the increment of the electrolyzer electricity consumption and before the curtailment (in Figure 65) starts increasing exponentially with the cost.

Thus, with this obtained outcome, it has been concluded that the most efficient solar PV installed capacity / electrolyser capacity ratio in the Valencian Community is 2.33 which means that this standard installation will have a 2.33 MWp solar PV capacity.

Mijares – Plana de Castellón

Using the PV tool of Solargis, it is possible to calculate the expected hourly average electricity production of a PV solar plant through the months of the year of a standardized PV solar plant of 2.33 MWp using single axis trackers with a relative separation of 2.5 meters. Solargis is able to calculate the area as well that it would need which in this case is around 15070 m^2.

However, it is important to consider that the electrolyzer can consume up to 1030 kWh and hence curtailment in the installation must be taken into account. Therefore, one can see in the Annex B the PV electricity production of the installation (see Table 18) depending on the day and hour. Additionally, this table has been replicated in Annex C (see Table 21) considering the effect of curtailment.

Summing all the columns we obtain the production of an average day of each month which afterwards is multiplied by the number of days of each month to calculate the monthly electricity production as seen in Table 14.

Table 14. Monthly average production Mijares - Castellón de la Plana

DC input	Jan	Feb	Mar	Apr	May	Jun
Daily	6595.1	8640.0	9959.2	11247.9	12088.9	12631.9
Monthly	204446.8	241919.6	308735.9	337437.2	374755.8	378958.3
DC input	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Daily	12380.8	11464.0	10210.7	8913.6	6808.6	5681.2

Monthly	383805.4	355383.7	306322.0	276322.7	204256.7	176115.8

Considering these numbers, it results in an electrolyzer annual electricity consumption of 3548460.1 kWh/year (3.55 GWh/year).

Turia

Using the same procedure to calculate the electricity production of a 2.33 MWp solar PV plant but in the location 2, we can obtain the Table 19 (Annex B) which, accounting for the curtailment results in Table 22 (Annex C).

Summarizing all the data in days and months, one can obtain the Table 15 similar as in the previous case.

Table 15. Monthly average production. Turia

DC input	Jan	Feb	Mar	Apr	May	Jun
Daily	6856.6	8684.9	9956.0	11219.3	12082.3	12565.8
Monthly	212554.0	243178.0	308637.5	336579.6	374550.5	376972.8
DC input	Jul	Aug	Sep	Oct	Nov	Dec
Daily	12407.5	11477.9	10274.5	8986.8	7084.3	5941.5
Monthly	384633.9	355814.3	308235.1	278589.4	212528.2	184187.4

Due to the slightly higher GHI of the location 2 in comparison to the location 1, the annual electricity consumption of the electrolyzer increases up to 3576460.7 kWh/year (3.58 GWh/year.).

Vinalopó - Alacantí

Finally, for the location 3 the process is replicated obtaining the results shown in Table 20 with the total PV electricity potential and Table 23 applying the curtailment to every day that the power is greater than the maximum electrolyzer capacity.

Summarizing all the data in days and months, one can obtain the Table 16 similar as in the previous case.

Table 16. Monthly average production. Vinalopó - Alacantí

DC input	Jan	Feb	Mar	Apr	May	Jun
Daily	7088.0	8761.3	9951.0	11179.1	12036.7	12585.2
Monthly	219727.7	245316.4	308481.5	335374.3	373139.2	377554.9
DC input	Jul	Aug	Sep	Oct	Nov	Dec
Daily	12343.7	11484.6	10327.7	9054.0	7159.3	6085.5
Monthly	382654.1	356023.9	309832.1	280673.5	214778.3	188651.6

Location 3 had the highest GHI among the most suitable locations and hence the greater annual electricity consumption of the electrolyzer with 3592207.7 kWh/year (3.59 GWh/year).

Hydrogen production

Once the two main inputs of the electrolyzer have been calculated, i.e. water availability and renewable electricity production, it is possible to calculate the potential tons of green hydrogen that 1MW electrolyzer facility could be able to produce.

Mijares – Plana de Castellón

In order to calculate the quantity of hydrogen produced with the available 3548460.1 kWh/year of electricity from the solar PV power plant one has to consider the power consumption of the electrolyzer and all the auxiliary subsystems needed for its proper function, also known as Balance of Plant (BoP). The BoP includes the water purification system, fan cooler, chiller, control panel and hydrogen purifier among others.

The H2B2 PEM electrolyzer has a BoP consumption of 5.1 kWh/Nm^3 equivalent to 56.74 kWh/kg.

Therefore, the annual production can be calculated as:

$$\text{Annual } H_2 \text{ production} = \frac{3548460.1\ kWh/year}{56.74\ kWh/kg_{H2}} = 62536.09\ kgH_2/year \tag{13}$$

Since 1 kg of H_2 is equivalent to 11.126 Nm^3 of H_2, with the available renewable electricity it is possible to produce 695776.48 Nm^3 of H_2/year.

The PEM electrolyser of H2B2 has an optional water treatment plant that purifies network-supplied water to the parameters required in the electrolyzer input and hence no other electricity consumption is accounted in this case.

According to [32] it has been concluded as an acceptable rule of thumb to consider 1.5 m^3 of surface water to produce 1 m^3 of ultrapure water. Since the EL200N electrolyzer requires 1 L/Nm^3 of H_2:

$$\text{Raw water required} = 695776.48\ \frac{Nm^3 \text{of } H_2}{\text{year}} \times 1\, \frac{L\ of\ demi\ water}{Nm^3 \text{of } H_2} \times 1.5\ \frac{L\ of\ surface\ water}{L\ of\ demi\ water} = 1043664.73\ \frac{L\ of\ surface\ water}{year} = 1043.665\ \frac{m^3\ of\ surface\ water}{year} \tag{14}$$

It is worth to mention that the energy required for the potabilization process from surface water to network-supplied water has been neglected due to its insignificant impact on the result [72].

Therefore, with a 1 MW electrolyzer and 2.33 MWp solar PV plant installed in the location 1 it would be needed 1043 m^3 of surface water to produce 62.5 tons of green H_2 per year which is less than 0.01% of the available water resources in the Mijares – Plana de Castellón system.

Turia

As shown in section 0 Turia, there is no water available for green hydrogen production in the water resource of the Turia system. Therefore, the only possibility to produce green hydrogen without compromising other sectors is to bring the water from a water desalination plant of another water resources management system.

The closest desalination plant to the Turia system is the desalination plant of Sagunto. Although physically the desalinated water will not go directly into the electrolyzer, it will be used to supply part of the demand of the Turia system and hence there would be surplus of water in the system available for green hydrogen production.

A 2.33 MWp solar PV plant in the location 2 would produce 3576460.7 kWh/year which, without considering the energy required for water desalination would be able to produce 63 tons of H_2 per year.

$$\text{Annual } H_2 \text{ production} = \frac{3576460.7\ kWh/year}{56.74\ kWh/kg_{H2}} = 63029.55\frac{kg_{H2}}{year} = 701266.8\frac{Nm^3 H_2}{year} \tag{15}$$

In this case there are two sources of water involved. The water supplied by the desalination plant to the Turia management system to maintain the balance of water resources, and the actual water consumed by the facility. The nearest water source to the location 2 is the Turia river and hence it will be assumed as network-supplied water similarly to the case in location 1.

The quantity of demi water required from the Turia river for the electrolysis can be calculated as follows:

$$\text{Demi water required} = 701266.8\ \frac{Nm^3 \text{of}\ H_2}{\text{year}} \times 1 \frac{L\ of\ demi\ water}{Nm^3 \text{of}\ H_2} = 701266.8\ \frac{L\ of\ demi\ water}{year} \quad (16)$$

According to [73], the energy consumption per m[3] of desalinated water produced of the Sagunto desalination plant is 4.28 kWh with a design conversion rate of 55%. Since the same amount of treated water needs to be replaced in the system:

$$\text{Raw water required} = 701266.8\ \frac{L\ of\ demi\ water}{year} \times \frac{1\ L\ of\ seawater}{0.55\ L\ of\ demi\ water} = 1275.03\ \frac{m^3\ of\ seawater}{year} \quad (17)$$

1275.03 m[3] of seawater would be required to be desalinated which would consume from the PV facility:

$$\text{Electricity needed for water desalination} = 1275.03\ \frac{m^3\ of\ seawater}{year} \times \frac{0.55\ m^3\ of\ demi\ water}{1\ m^3\ of\ seawater} \times 4.28\ \frac{kWh}{m^3\ of\ demi\ water} = 3001.42\ kWh/year \quad (18)$$

Since this electricity would come from the PV installation and hence needs to be subtracted from the electricity available for the water electrolysis, an iterative process is needed where the green hydrogen production is recalculated.

$$\text{Annual } H_2 \text{ production} = \frac{3576460.7\frac{kWh}{year} - 3001.42\frac{kWh}{year}}{56.74\ kWh/kg_{H2}} = 62976.66\frac{kg_{H2}}{year} = 700678.29\frac{Nm^3 \text{of}\ H_2}{\text{year}} \quad (19)$$

Water from the Turia river:

$$\text{Demi water required} = 700678.29\ \frac{Nm^3 \text{of}\ H_2}{\text{year}} \times 1 \frac{L\ of\ demi\ water}{Nm^3 \text{of}\ H_2} = 700678.29\ \frac{L\ of\ demi\ water}{year} \quad (20)$$

Water from the Sagunto desalination plant:

$$\text{Raw water required} = 700678.29\ \frac{L\ of\ demi\ water}{year} \times \frac{1\ L\ of\ seawater}{0.55\ L\ of\ demi\ water} = 1273960.5\ \frac{L\ of\ seawater}{year} \quad (21)$$

$$\text{Electricity needed for water desalination} = 1273.961\ \frac{m^3\ of\ seawater}{year} \times \frac{0.55\ m^3\ of\ demi\ water}{1\ m^3\ of\ seawater} \times 4.28\ \frac{kWh}{m^3\ of\ demi\ water} = 2998.90\ kWh/year \quad (22)$$

If the iterative process is repeated, it will end up with the same results which means that the results from the first iteration can be assumed as accurate enough. Therefore, one can conclude that the water treatment would require 1273.96 m[3] from the Mediterranean Sea which would need 2998.9 kWh/year for its treatment.

To sum up, a 2.33MWp solar PV plant and 1MW PEM electrolyzer located in the Turia system could produce 62.98 tons of green hydrogen per year.

Vinalopó – Alacantí

For the first hydrogen production approximation, the procedure is the same as in the previous locations dividing the electricity produced in a year in the solar PV power plant by the power consumption of the electrolyzer.

$$\text{Annual } H_2 \text{ production} = \frac{3592207.7\ kWh/year}{56.74\ kWh/kg_{H2}} = 63307.07 \frac{kg_{H2}}{year} = 704354.45\ Nm^3 H_2/year \quad (23)$$

As stated in section 0, the only possibility to obtain water for green hydrogen production in the location 3 without competing with other sectors is the available water coming from the desalination facility in Alicante.

The desalination facility next to the location is formed by two plants, Alicante I and Alicante II which according to [68], they have an energy consumption rate of 5.06 and 3.75 kWh/m^3 of desalinated water respectively. Additionally, the efficiency of both plants is below the 50%, having a 42% conversion rate Alicante I and a 45% Alicante II [68].

Since the water will be produced by any of the plants which is available at the moment because other demands are prioritized, in this section the average values of both installations will be used. The combined facilities have a specific energy consumption of 4.4 kWh/m^3 and a 43.5 % conversion rate.

Therefore:

$$\text{Raw water required} = 704354.45 \frac{Nm^3 \text{of } H_2}{\text{year}} \times 1 \frac{L\ of\ demi\ water}{Nm^3 \text{of } H_2} \times \frac{1\ L\ of\ seawater}{0{,}435\ L\ of\ demi\ water} = 1619205.62 \frac{L\ of\ seawater}{year} = 1619.205 \frac{m^3\ of\ seawater}{year} \quad (24)$$

The calculated quantity of seawater will require the following energy for desalination:

$$\text{Electricity needed for water desalination} = 1619.205 \frac{m^3\ of\ seawater}{year} \times \frac{0.435\ m^3\ of\ demi\ water}{1\ m^3\ of\ seawater} \times 4.4 \frac{kWh}{m^3\ of\ demi\ water} = 3102.68\ kWh/year \quad (25)$$

Once the first approximation is obtained, another iteration is needed in order to calculate a most accurate hydrogen production accounting for the energy needed for the water desalination.

$$\text{Annual } H_2 \text{ production} = \frac{3592207.7\frac{kWh}{year} - 3102.68\frac{kWh}{year}}{56{,}74\ kWh/kg_{H2}} = 63252.39 \frac{kg_{H2}}{year} = 703746.08 \frac{Nm^3 \text{of } H_2}{\text{year}} \quad (26)$$

$$\text{Raw water required} = 703746.08 \frac{Nm^3 \text{of } H_2}{\text{year}} \times 1 \frac{L\ of\ demi\ water}{Nm^3 \text{of } H_2} \times \frac{1\ L\ of\ seawater}{0.435\ L\ of\ demi\ water} = 1617807{,}07 \frac{L\ of\ seawater}{year} \quad (27)$$

$$\text{Electricity needed for water desalination} = 1617.807 \frac{m^3\ of\ surface\ water}{year} \times \frac{0.435\ m^3\ of\ demi\ water}{1\ m^3\ of\ seawater} \times 4.4 \frac{kWh}{m^3\ of\ demi\ water} = 3100\ kWh/year \quad (28)$$

This approximation is accurate enough since another iteration would end up in the same results. Thus, installing a combined 1MW electrolyzer and 2.33MWp PV plant facility next to the desalination plant in location 3 would allow a production of 63.25 tons of green hydrogen per year and would require 1617.8 m^3 of seawater.

Hydrogen storage

The actual demand of hydrogen in each facility is not set in the scope of this thesis and hence the hydrogen produced is assumed to be stored in a weekly production basis in tanks at the electrolyzer output pressure i.e., 40 bar.

The selected tank for the facility has a capacity of 180 kg of H_2 at a 40 bar pressure. Depending on the facility the weekly production will be between 1202 and 1217 kg of H_2.

$$\frac{1202}{180} = 6.68; \frac{1217}{180} = 6.76;$$

This means that at least there will be a need of 7 LH50H tanks in each facility in order to store their weekly production.

3.5.3 Scaled facility

Now that the analysis has been done to the 1 MW electrolyzer facilities in the different sites and unitary values have been calculated, it is possible to scale the standarized facility according to the water availability in each different water resource management system.

Since in the 1 MW facility the electrolyzer was producing hydrogen only during the sunlight hours, the water requirements were low which would lead to an enormous capacity of the electrolyzer in order to harness the 100% of water available. Additionally, the electrolyzer is the most expensive part of the facility and hence it is interesting to have it operating the maximum possible amount of time. In order to do that in this section a renewable PPA is integrated in the equation so that the electrolyzer can be working twenty-four hours a day and consume the maximum water available making the peak capacity required (both PV and electrolyzer) as low as possible.

Nevertheless, it is important to highlight that this approach has several limitations. It is only meant to give a general overview of the total potential of each area and a deeper analysis must be done considering several factors such as the economies of scale, environmental impact in the area, impact and limitations on the supply-water net, variability of the electricity/hydrogen generation or the possibility to sell the surplus electricity generation to the grid.

In the location 1, the 1MW facility could produce 62.5 tons of H_2/year with a surface water usage of 1043 m^3 per year. Considering that in this area the total water available is 14.97 hm^3/year, the potential hydrogen production is more than 14000 times i.e., 896998 tons of green hydrogen/year.

From the EL200N datasheet we can assume that the 24h production of the 1MW electrolyzer is 430kg/day which operating the 365 days of the year means 156.95 tons of H_2 per year.

$$\text{Required electrolyzer capacity} = \frac{896\,998\ tons\ of\ H_2}{156.95\ tons\ of\ H_2/MW} = 5715.18\ MW \quad (29)$$

Therefore, in order to harness the 14.97 hm^3/year of water available in the region a 5.72 GW electrolyzer would be needed.

For the location in the Turia exploitation system as stated in previous sections there is no water available for green hydrogen production if other systems are not involved. Therefore, since it would depend on a lot of scenarios and different possibilities, it has been considered not possible to determine a possible potential different than the maximum capacity of the Sagunto desalination plant. Its production capacity is 8.2 hm^3/year [73] which in terms of seawater is 14.91 hm^3/year. This would imply a potential of 403842.41 tons of green hydrogen per year.

$$\text{Required electrolyzer capacity} = \frac{403842.41\ tons\ of\ H_2}{159.95\ tons\ of\ H_2/MW} = 2573.06\ MW \quad (30)$$

In order to produce that quantity of hydrogen, 2.57 GW of electrolyzers would be required to be installed in the Turia region.

Finally, the third location has only available the remaining capacity of the Alicante desalination plants after supplying the rest of the demands i.e., 10.22 hm^3/year which applying the average conversion rate turns into 23.49 hm^3 of seawater/year. Thus, the potential green hydrogen production in this case is multiplied by 14522 times resulting in a total potential of 918569.12 tons of green hydrogen per year which according to the equation below would assume a maximum of 5.85 GW of electrolyzers.

$$\text{Required electrolyzer capacity} = \frac{918569.12\ tons\ of\ H_2}{159.95\ tons\ of\ H_2/MW} = 5852.62\ MW \quad (31)$$

3.6 Economic assessment

In this section an economic assessment of the three different facilities will be done by calculating the levelized cost of hydrogen (LCOH). The LCOH is a parameter that helps to compare different facilities and technologies of hydrogen production by quantifying the costs of producing 1 kg of hydrogen. The costs involved are both the Capex and Opex which in this case include the PV plant and the electrolyzer.

The following equation shows how the LCOH is calculated:

$$LCOH = \frac{\sum_{t=0}^{t=T} \frac{C_{capex} + C_{opex}}{(1+r)^t}}{\sum_{t=0}^{t=T} \frac{M_{H2}}{(1+r)^t}} \quad (32)$$

being:

- C_{capex} the total investment cost of the facility including the water treatment plant, the PV plant, the electrolyzer and its equipment and the hydrogen storage in €/year.
- C_{opex} the operation and maintenance costs of each installation mentioned before in €/year.
- M_{H2} the annual hydrogen production in kg/year.
- T the lifetime of the facility in years.
- r the discount rate.

In Table 17, a summary of the parameters used in the economic assessment is shown.

Table 17. Parameters values used in the economic assessment

Parameter	Unit	Value	Source
Electrolyzer parameters			
Power (BoP + Stack)	kW	1 030	[74]
Capital cost	€	1 350 000	Estimation
Operating costs	€ + €/kW/year	15 + 5	[75]
Yearly degradation	%	0.3	[76]
Electrolyzer lifetime	years	20	[77]
Stack lifetime	hours	40 000 – 60 000	[78]
Stack replacement cost	% of capital cost	40	[76]
PV parameters			

Peak power	MWp	2.33	Own analysis
Capital cost	€/Wp	0.54	[79], [80]
Operating costs	€/kWp/year	8	[81]
1st year degradation	%	2	[82]
Subsequent years degradation	%	0.55	[82]
Hydrogen storage			
Capacity	kg of H_2/tank	180	[83]
Pressure	bar	40	[83]
Storage time	time	Weekly	Estimation
Capital cost	€/ud	105 200	[83]
Surface water (location 1)			
Operating costs	€/m^3	0.57	[84]
Surface water (location 2)			
Operating costs	€/m^3	0.583	[85]
Desalination and water transportation (location 2)			
Operating costs	€/m^3	1.3	[86]
Pipe capital cost	€/m	3.02	[87]
Pipe length	km	23.8	Estimation
Desalination (location 3)			
Operating costs	€/m^3	1.3	[86]
General parameters			
Facility lifetime	years	20	-
Discount rate	%	3.23	[88]

In the location 1, the water consumed can be acquired at a price of 0.57 €/m^3 because it would be an industrial consumption [84]. Since the electrolyzer has the possibility to add a reverse osmosis installation, no other capex or opex will be included in this section.

In Annex D (Table 24) all the costs involved in the location 1 LCOH calculation are detailed throughout the 20 years lifetime of the green hydrogen production facility.

The LCOH obtained is 4.54 €/kg which is distributed as shown in Figure 67.

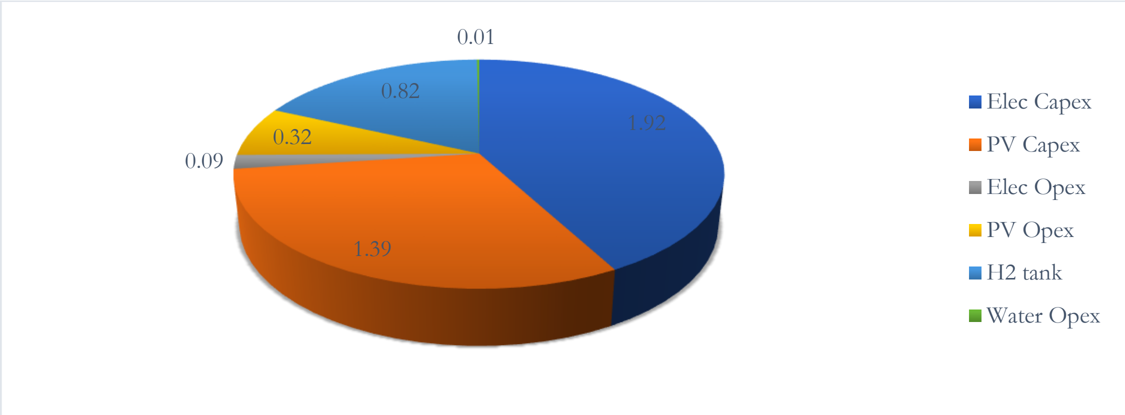

Figure 67. LCOH distribution among different parameters of site 1

Location 2 has two parameters associated to water costs. The first one is the water price of the actual water used for the electrolysis which would come from the supply-water net of the city, and the second one which is the costs associated with the treated water from the Sagunto desalination plant and the infrastructure to transport the water to the Turia system.

The pipe needed for transferring the desalinated water from Sagunto to Valencia has been estimated to be 23.8 km. Since the water flow from the desalination plant would be 0.14 m^3/h and 1 m/s is commonly used as the design velocity for water transportation, using equation 14 it has been concluded that the pipe needed has a DN6 diameter.

$$v = \frac{Q_w}{3600\pi(\frac{d}{2})^2} \rightarrow \mathrm{d} = 7\mathrm{mm} \qquad (33)$$

The construction of this pipe is budgeted to be 3.02 €/m in Spain [87].

As one can see in Annex D (Table 25), the LCOH in this case is 4.63 €/kg which is distributed as shown in Figure 68.

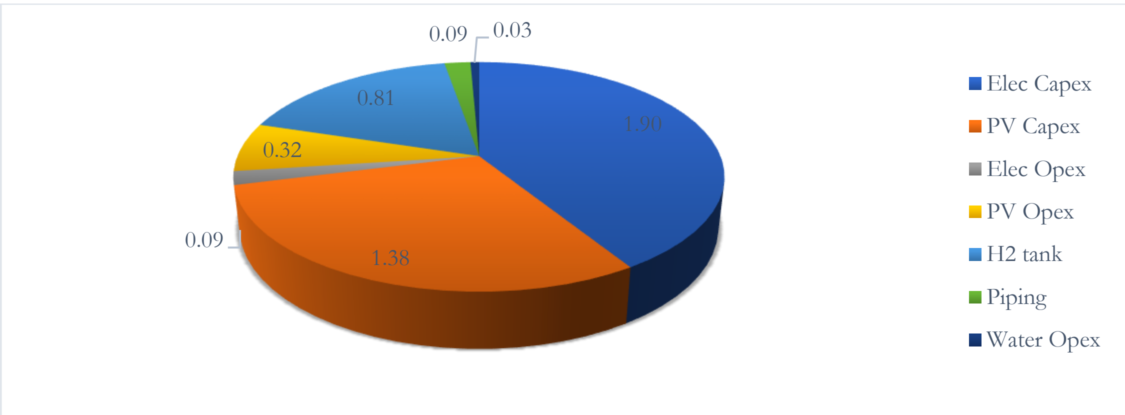

Figure 68. LCOH distribution among different parameters of site 2

Finally, the costs of the location 3 are analyzed as depicted in Table 26 (Annex D). Since this location is next to the desalination plants, the only costs related to the water is the price for the desalinated water (see Figure 69).

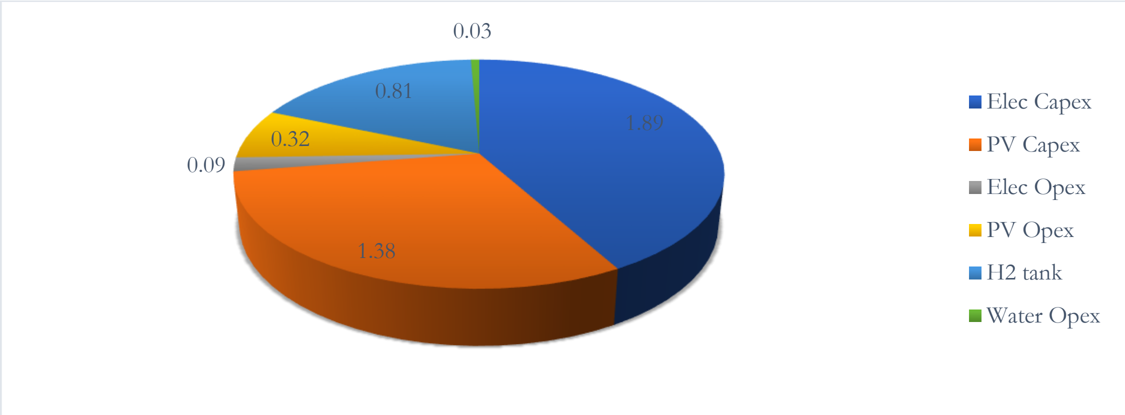

Figure 69. LCOH distribution among different parameters of site 3

4 Results

After having developed the methodology for identifying the most suitable locations for green hydrogen production in the Valencian Community and performed an analysis of its potential in three different sites, in this section the results found are presented.

Firstly, in Figure 70 the final suitability map is presented with the location of the three different facilities and its green hydrogen potential production with a 1 MW electrolyzer and 2.33 MW PV plant.

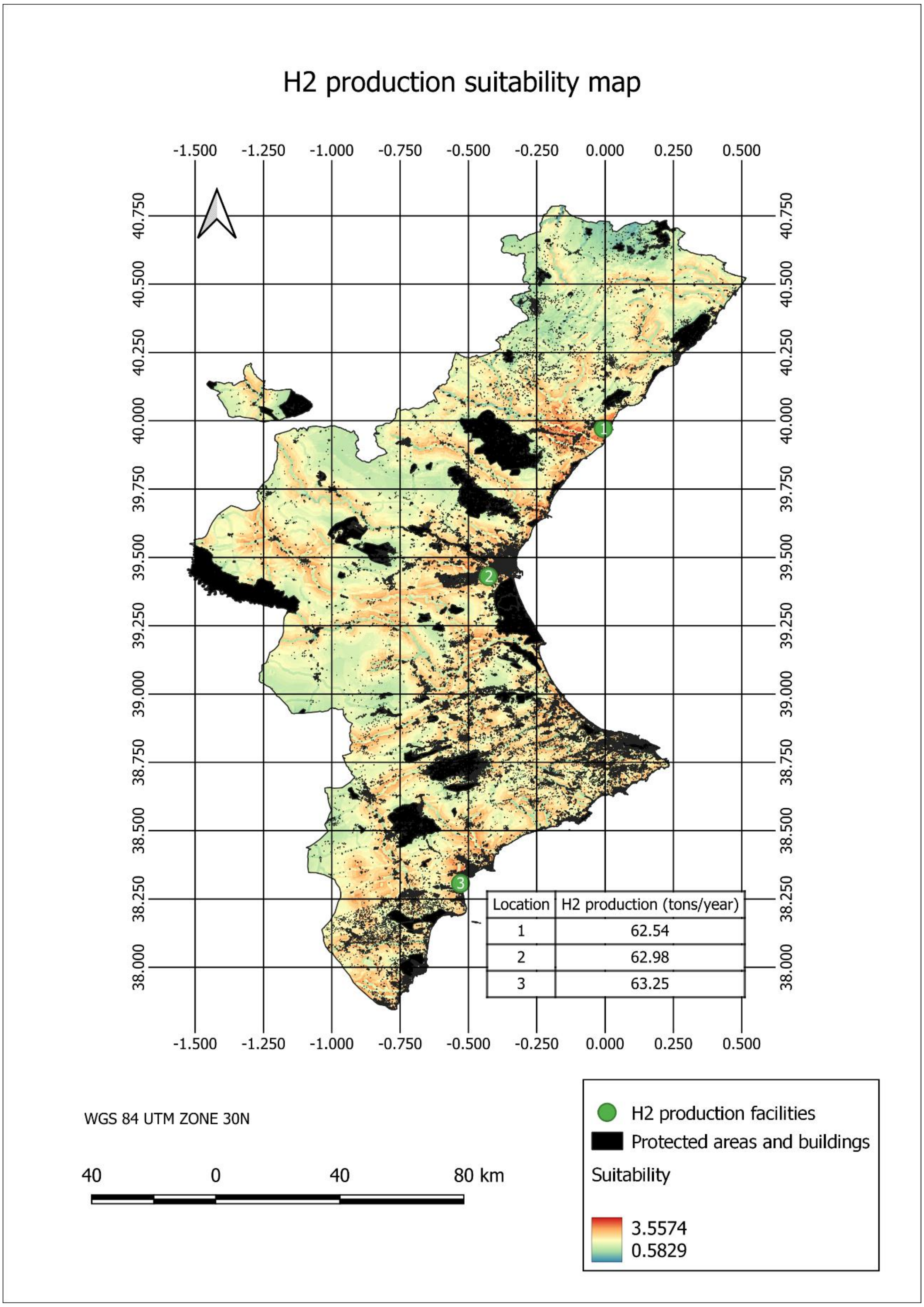

Figure 70. H2 production suitability map

When comparing the three facilities in terms of tons of hydrogen produced yearly, one can see in Figure 71 that the difference in relative terms is not significant. Specifically, the gap between the first site which has the lower production and the third site having the higher production is within a range of 1.21 %.

This similarity in terms of hydrogen production can be due to several reasons. Firstly, because the H_2 production is directly related to the electricity production and since the radiation in the region is homogeneous, the electricity potential is really similar in every site. Secondly, another factor that influences directly to the hydrogen production is the availability of water and in the three cases for a 1MW electrolyzer a solution has been found to obtain enough water for producing almost the same quantity of H_2 in each site.

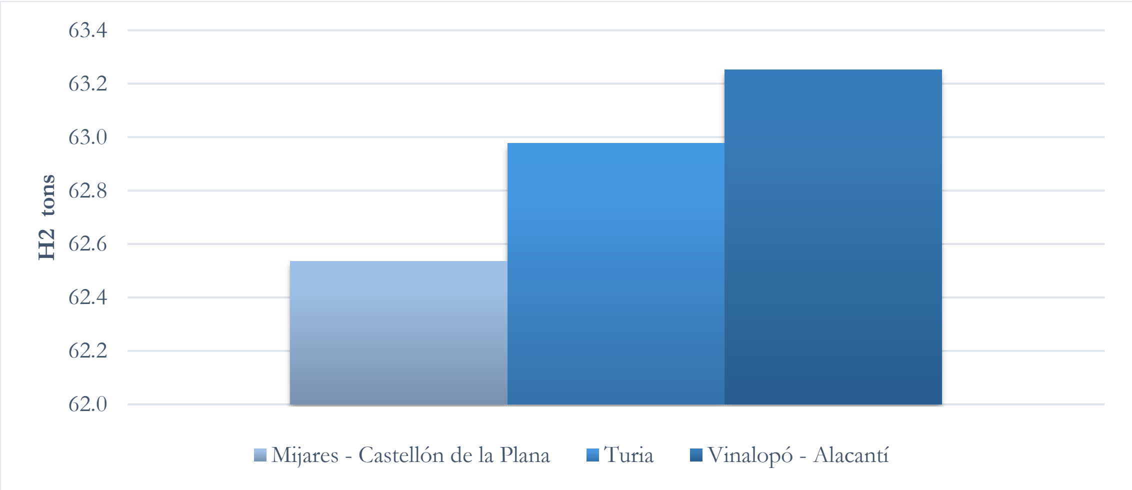

Figure 71. H2 production comparison in different sites

As stated in the previous comparison, the electricity production in each site is very similar due to the homogeneous radiation in the Valencian Community region. Therefore, the production in the site with the highest level of radiation is only 1.23% higher than the electricity production in the site with the lowest level of radiation.

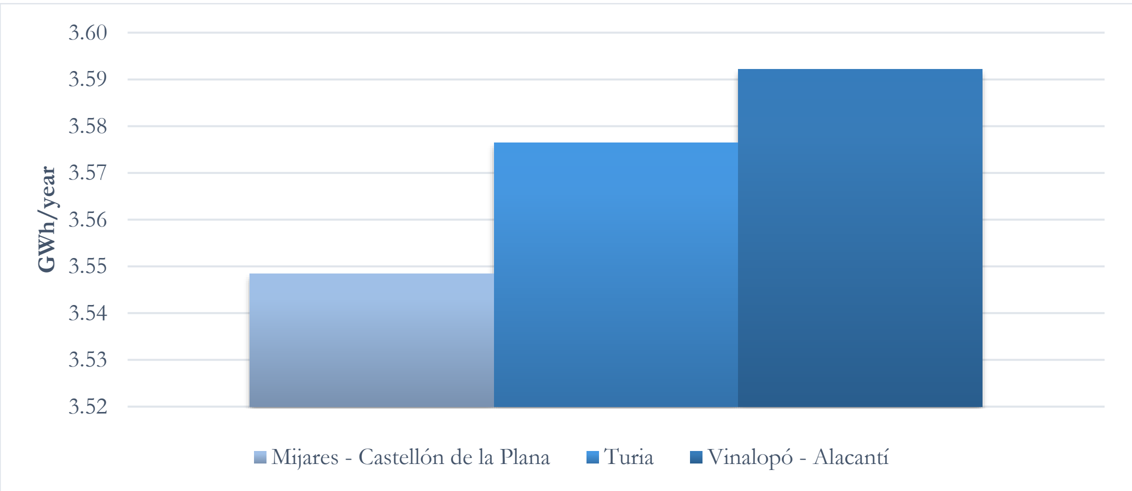

Figure 72. PV electricity production comparison in different sites

Another interesting factor to look at when comparing green hydrogen production facilities is the raw water required to perform the electrolysis.

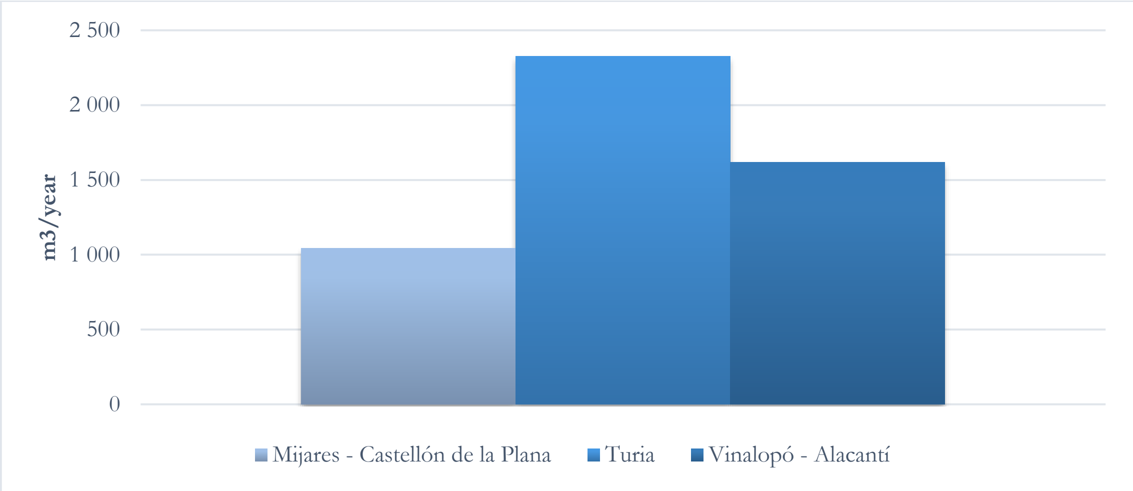

Figure 73. Raw water required comparison in different sites

Looking at Figure 73 it is clear that the facility in the location 2 requires more than two times the raw water in the location 1 because it accounts for both the water taken from its resource water management system and from the neighbouring system to keep the water balance in equilibrium.

When it comes to the greater consumption of the location 3 in comparison to the location 1 is due to the higher raw water required in a desalination plant since the process of transforming seawater to demineralized water has a lower efficiency than purifying surface water.

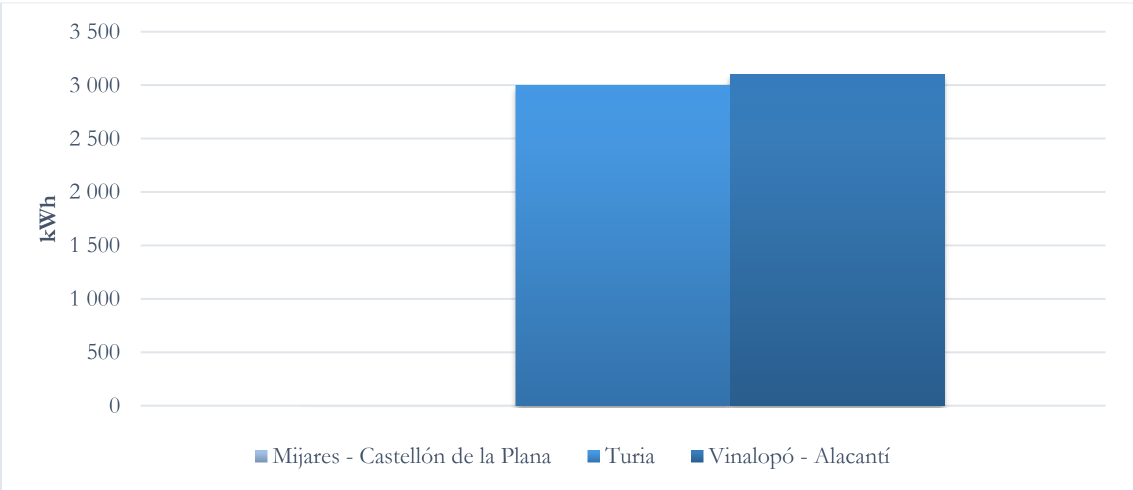

Figure 74. Energy required for water treatment comparison in different sites

Although a water purification process is performed in the first location, it is included in the electrolyzer BoP consumption and hence it does not appear in Figure 74. The figure sows the similarities between locations 2 and 3 only differentiated by the efficiency of the desalination plants.

The same happens with Figure 75. However, in this graph is interesting to depict that the share of electricity consumed by the water treatment system of the hydrogen production facility is in the worst case only 0.086 % of the total electricity produced.

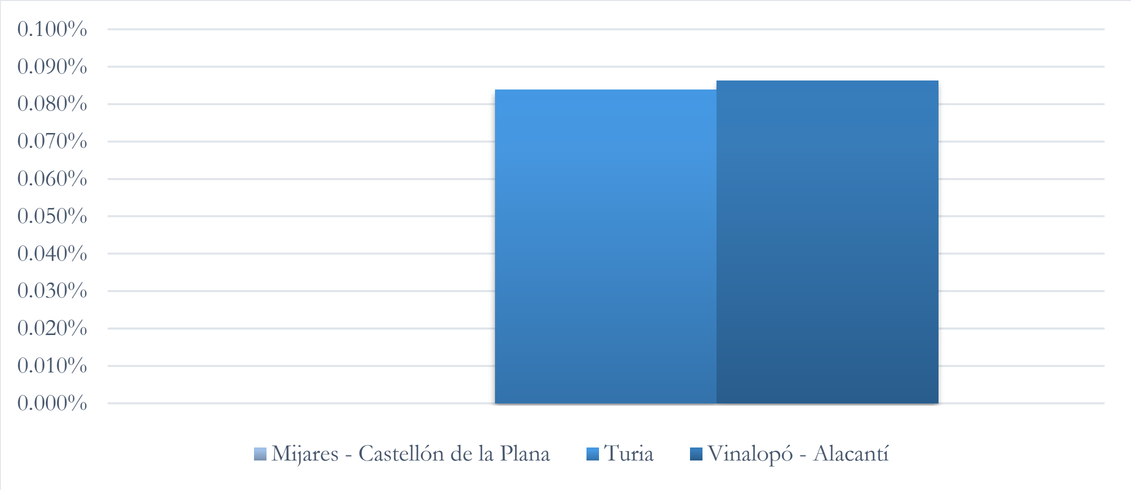

Figure 75. Share of PV electricity used for the water treatment comparison in different sites

The last parameter compared is the levelized cost of hydrogen which ranges from 4.51 €/khH_2 in the third location to 4.63 €/khH_2 in the second location (see Figure 76). This is, 2.63% greater the most expensive in comparison to the cheapest option.

It is worth noting in this section that a study of hydrogen production by water electrolysis and off-grid solar PV in Madrid carried in 2021 ended with the conclusion that the LCOH in that study case was around 6 – 7 €/kg [89], However, this difference of around 40% of the LCOH is mainly influenced by the economies of scale and the rapidly decrement in PV and electrolyzers costs during the last years.

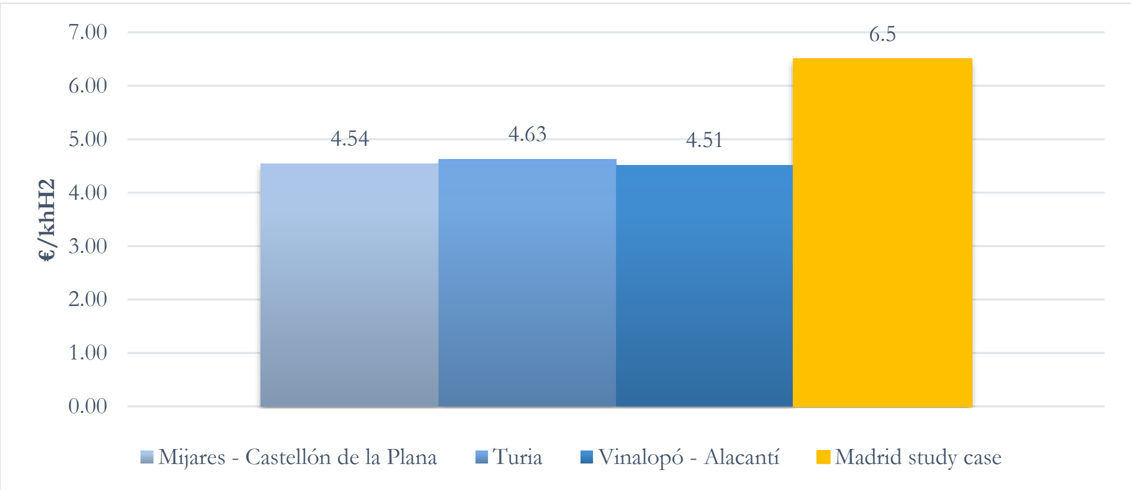

Figure 76. LCOH comparison in different sites

As one could expect, the differences of LCOH among the facilities in the Valencian Community are relatively small since the three of them have a similar electricity production and all the water that the electrolyzer can consume available.

The second location results in the highest LCOH due to the need of water piping from one exploitation system to another and the water acquisition costs are accounted twice. Moreover, the reason for the third location being the cheapest is due to the higher production of electricity. Although the water opex costs in the third location are more than 3 times higher than in the first one, the total costs only differ in a 0.47% and the hydrogen production is 1.21% higher resulting in a 0.74% lower LCOH for the facility in the location 3 in comparison to the facility in the location 1.

4.1 Sustainability and ethical aspects of the work

Sustainable development is “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [90]. A frequent way to approach this concept is to illustrate it in terms of dimensions: ecological, social and economic sustainability. These dimensions are usually described within a Venn diagram where the three dimensions overlap each other having all of them equal importance [91].

The methodology developed in this study can ensure that hydrogen production is carried out in an ecological sustainable way considering several variables including land availability, proximity to sources of clean energy and water or other potential environmental sensitivities.

The economic sustainability dimension is also involved in the study by considering economic factors in the site suitability assessment. However, the social dimension is not directly approached in this study. In order to impact this dimension, some layers that evaluates any potential advantages for neighbourhood communities such as job growth or improved access to energy could be included in the methodology.

When it comes to the core objectives of sustainable development, this thesis contributes to the environmental integrity of the chosen locations by considering factors such as land use and water availability. Additionally, intra-generational and inter-generational equity are also considered when evaluating the current state of the natural resources and the potential depletion of them due to the green hydrogen production in each site.

Compared to traditional methods, green hydrogen production offers significant environmental advantages directly related to the United Nations Sustainable Development Goals (UN SDGs). Utilizing renewable energy sources such as solar PV or wind power lowers greenhouse gas emissions, aiding in the pursuit of affordable, clean energy (SDG 7) and climate action (SDG 13). Additionally, it enhances air quality, supporting SDG 3 for good health and wellbeing as well as SDG 11 for sustainable cities and communities.

Assessing the most suitable locations for green hydrogen production will lead to minimize energy losses and enhance responsible consumption and production (SDG 12). Moreover, including the potential industrial consumption as a layer contributes to SDG 9 industry, innovation, and infrastructure.

While using the methodology to analyze the most suitable location one can also look at the impact that green hydrogen technology spread in the region will have on creating employment opportunities, promoting decent work and economic growth (SDG 8).

When it comes to ethical considerations, equitable access to green hydrogen technologies is crucial to enable social inclusion and to help the reduction of disparities (SDG 10). This includes fair labour practices, transparent supply chains, and responsible sourcing, which all contribute to the SDGs of peace, justice, and strong institutions (SDGs 12 and 16).

Finally, regulations and policies are crucial in promoting ethics and sustainability through any sector. Therefore, to encourage the development of green hydrogen and foster collaborations for the goals, governments and international organizations must establish supportive frameworks (SDG 17).

5 Conclusions and future work

This master thesis aimed to develop a methodology that allows to give a proposal of the most suitable locations of green hydrogen production facilities and their production potential based on the sun, wind and water resources as well as the transportation infrastructures and main hydrogen potential consumers within the Valencian Community.

This has been achieved by establishing four main steps in the methodology which can be divided into data acquisition for the layers' creation and preprocess, AHP for the weights' allocation, and multi-criteria weighted overlay analysis and water availability assessment for grading the site suitability.

Additionally, while developing the methodology it has been performed a real case in the Valencian Community where the three most suitable sites based on the selected criteria have been identified. By identifying these sites, the secondary goal of the thesis has been fulfilled which was to determine the hydrogen production potential of those locations considering their available natural resources.

Once the calculations were done some conclusions could be drawn about the methodology and some future work was identified.

The AHP integrated with the MCWOA method resulted in a better approach over a linear optimization. Since there was a lack of enough data about the national gas pipeline network and amount of potential demand it was not possible to optimally allocate the hydrogen production to the different potential customers through a linear optimization methodology.

Interesting findings have been identified once the suitability map was formed such as the major importance of the proximity of the suitable sites to waterbodies due to its impact on the LCOH and in the environment and supply-water network infrastructures, or the relatively low significance of the solar radiation when comparing sites in a region similar to the Valencian Community due to its homogeneity. Additionally, it could be interesting to reassess the weight of each layer after identifying the missing needs of each suitable site which would change the suitability score of each location.

Adding more layers to the overlay process such as the national gas pipeline network would add a lot of value to the methodology due to the possibility of performing hydrogen blending. However, it is important to note that the change in the suitability map would be only significant if the importance given to the layer or the number of layers added is high enough. The map and hence the results would change as well when including other sources of renewable electricity such as PPAs and other layers such as one referring to the cadastral value of land.

In the methodology, the water balance was performed after the creation of the site suitability map. However, after assessing the hydrogen production in the different sites it has been depicted that it would have been more efficient to include the water balance in a layer format in the overlay step.

When discussing about increasing the scope of the methodology by applying it to another region or scaling it up to a greater one, it is important to note that the layers have been selected based on the socio-economic and geographical characteristics of the Valencian Community and hence these parameters should be reassessed since some criteria may be not significant for the new scope and new criteria may arise.

To conclude, it can be said that in this master thesis a methodology for assessing the site suitability for green hydrogen production has been developed and proven its efficacy by analysing three study cases with different characteristics in the Valencian Community. Nevertheless, due to the limitation of being a master thesis there is still room for future work by using more accurate georeferenced data, perform some sensitivity analysis on the layers' weights or analyse the possibility to add more layers or sources of renewable electricity to the study.

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Annex

A. Electrolyzer datasheet

Main Characteristics	EL200N
Electrolysis Type	PEM (Proton exchange membrane, caustic free)
Number of Cell Stacks	1
Hydrogen Gas Production	
Max. Nominal Hydrogen Flow	200 Nm^3/h (430 kg/day)
Hydrogen Flow Range	10 -100%
Operating Pressure	15 - 40 barg (217-580 psig)
Hydrogen Purity (before Gas Purification)	> 99.9% ; < 25 ppm O_2; H_2O saturated
Hydrogen Purity (after Gas Purification)	99.999%; < 5 ppm O_2; < 5 ppm H_2O
Electrical Requirements	
Voltage	3 x 400 VAC ± 10% (3Ph+N) / 3 x 480 VAC ± 10% (3Ph+N)
Frequency	50 Hz ± 5% / 60 Hz ± 3%
Power (BoP + Stack)	1,030 kW
Stack Consumption (*)	4.7 kWh/Nm^3 H_2
AC Power Consumption (BoP + Stack) (*)	5.1 kWh/Nm^3 H_2
Feed Water - Demi Water (optional Water Treatment Plant is not included)	
Consumption	< 1 L/Nm^3 H_2
Conductivity	> 10 MΩcm (< 0.1 uS/cm); TOC < 30 ppb
Pressure	2-3 barg (29-43 psig)
Temperature	+5 °C to +40 °C (+41 °F to +104 °F)
Control System	
PLC	Fully automated and unattended with 15" color touch screen
Communication	Modbus TCP/IP or Profinet (RJ45 port)
Environmental Conditions	
Ambient Temperature Range	+5 °C to +45 °C (+41 °F to +113 °F)
Humidity	0 to + 95% (non-condensing)
Air Ventilation	Available from a non-hazardous area
Installation Area	Indoor/Outdoor
Dimensions and weight	
Dimensions (LxWxH)	40 ft container (12.0m x 2.4m x 2.9m) (39.4ft x 7.9ft x 9.5ft)
Approx. Weight	18,000 kg (39,683 lb)
Standards & Regulations	
Compliance	CE, ISO 22734-1 / NFPA 2-2016 & NFPA 70
Other Characteristics	
Duty Cycle	100% (24/7)
Start-up Time (from Stand-by)	< 1 sec
Cold Start Time	< 5 min
Nitrogen System	For each purge, consumption is <0.2 kg at 3 barg (to be supplied by the customer)
Instrumentation Air System	Consumption 7 Nm^3/h at 10 barg (to be supplied by the customer)

(*) Electrical consumption at maximum current density and operating pressure at the stack; thus is reduced if those are not required.

Included	Additional Options
Hydrogen Cooling System	Oxygen Processing System
Emergency Shutdown System	Hydrogen Purification System (SAE J2719 September 2011)
Overpressure Relief System	Water Treatment System
Redundancy on Critical Safety Parameters	Extreme Environmental Conditions Package (Low and High Temp)
Uninterruptible Power Supply (UPS)	Hydrogen Mass Flow Measure & Purity Measure (H_2O & O_2 Sensors)
Heat Management (No Cooling Water is Needed)	Instrumentation Air System
Virtual Private Network (VPN) connection	Nitrogen System
	Heat Recovery System
	Medium Voltage Connection

B. PV electricity production in each suitable site

Table 18. DC electricity production Mijares - Castellón de la Plana (kWh)

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1 - 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2 - 3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3 - 4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4 - 5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5 - 6	0.0	0.0	0.0	0.0	1.3	5.5	0.7	0.0	0.0	0.0	0.0	0.0
6 - 7	0.0	0.0	0.0	21.4	188.9	284.9	179.6	43.3	2.4	0.0	0.0	0.0
7 - 8	0.0	0.0	67.7	468.3	784.8	885.8	772.8	519.8	259.0	59.5	0.6	0.0
8 - 9	27.9	172.2	647.1	1111.9	1204.6	1252.0	1207.5	1065.1	879.5	587.0	215.3	42.8
9 - 10	499.1	833.9	1141.9	1350.2	1420.0	1479.9	1452.2	1289.4	1178.2	1004	769.7	498.8
10 - 11	893.1	1079	1250.3	1456.0	1530.6	1614.8	1603.0	1423.4	1267.3	1067	891.3	807.0
11 - 12	900.7	1108	1303.2	1499.6	1578.7	1676.8	1659.5	1501.6	1331.1	1101	887.2	792.4
12 - 13	868.6	1102	1345.8	1518.4	1605.7	1687.5	1676.5	1529.8	1367.5	1118	879.6	765.0
13 - 14	856.6	1106	1358.9	1497.4	1606.4	1690.3	1688.0	1541.9	1375.3	1121.9	892.0	768.8
14 - 15	890.0	1108	1325.3	1462.2	1570.6	1672.5	1677.5	1555.8	1346.6	1100.1	902.0	802.6
15 - 16	904.4	1114	1286.3	1400.3	1503.2	1603.9	1639.1	1488.7	1248.8	1043.1	880.8	796.7
16 - 17	674.5	1040.7	1190.2	1283.3	1362.3	1481.7	1505.7	1332.7	1089.8	839.9	474.2	396.8
17 - 18	80.1	421.0	859.2	1027.4	1135.9	1245.0	1285.2	1098.5	721.3	216.2	15.8	10.4
18 - 19	0.0	2.9	145.2	441.4	706.8	870.8	873.5	562.0	108.5	1.1	0.0	0.0
19 - 20	0.0	0.0	0.0	16.9	107.1	279.3	251.7	38.8	0.0	0.0	0.0	0.0
20 - 21	0.0	0.0	0.0	0.0	0.0	5.6	2.4	0.0	0.0	0.0	0.0	0.0
21 - 22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22 - 23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23 - 24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sum	6595	9090	11921	14554	16306	17736	17475	14990	12175	9260	6808	5681

Table 19. DC electricity production. Turia (kWh)

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1 - 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2 - 3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3 - 4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4 - 5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5 - 6	0.0	0.0	0.0	0.0	0.0	2.2	0.0	0.0	0.0	0.0	0.0	0.0
6 - 7	0.0	0.0	0.0	20.2	175.8	255.2	161.0	25.9	0.5	0.0	0.0	0.0
7 - 8	0.0	0.0	39.8	448.4	777.7	844.7	758.4	487.5	248.9	50.2	0.6	0.0
8 - 9	29.5	144.3	624.3	1072.8	1207.4	1222.8	1207.2	1065.2	885.9	588.1	194.9	44.2
9 - 10	515.6	845.3	1162.5	1336.9	1409.3	1454.6	1429.2	1288.1	1194.6	1008	791.8	514.9
10 - 11	917.9	1096	1278.8	1446.0	1533.3	1584.3	1562.6	1419.4	1275.7	1087	921.4	834.1
11 - 12	929.9	1110	1317.7	1494.3	1601.7	1660.7	1646.2	1491.8	1312.0	1121	918.6	826.4
12 - 13	900.5	1108	1349.5	1510.7	1625.8	1697.2	1691.2	1545.5	1347.2	1128	911.9	792.9
13 - 14	891.0	1115	1363.5	1498.2	1614.8	1699.9	1704.8	1570.8	1363.7	1129	923.6	794.0

14 - 15	923.7	1125	1330.0	1493.5	1585.9	1679.3	1704.9	1575.3	1356.5	1123	947.0	833.7
15 - 16	933.9	1128	1286.8	1416.2	1518.3	1626.0	1665.0	1527.9	1294.2	1082	925.3	839.4
16 - 17	723.0	1064	1223.3	1314.6	1381.8	1495.8	1556.7	1407.2	1150.9	894.1	528.0	447.3
17 - 18	91.5	472.9	893.3	1054.7	1148.5	1272.9	1338.8	1156.0	778.7	243.2	21.1	14.4
18 - 19	0.0	12.5	158.5	440.6	718.3	881.5	921.2	608.6	120.5	1.1	0.0	0.0
19 - 20	0.0	0.0	0.0	10.1	110.3	278.8	263.8	55.9	0.0	0.0	0.0	0.0
20 - 21	0.0	0.0	0.0	0.0	0.0	3.4	3.1	0.0	0.0	0.0	0.0	0.0
21 - 22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22 - 23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23 - 24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sum	6856	9224	12028	14557	16409	17659	17614	15225	12329	9458	7084	5941

Table 20. DC electricity production. Vinalopó - Alacantí (kWh)

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1 - 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2 - 3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3 - 4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4 - 5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5 - 6	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0
6 - 7	0.0	0.0	0.0	7.1	144.3	240.5	131.5	24.8	0.5	0.0	0.0	0.0
7 - 8	0.0	0.0	39.4	421.2	771.3	861.0	752.7	496.6	227.0	53.3	0.6	0.0
8 - 9	49.6	182.8	633.4	1092.7	1252.9	1302.1	1246.8	1110.9	928.0	612.1	205.1	56.1
9 - 10	566.6	870.5	1189.9	1357.1	1479.4	1545.5	1508.9	1393.8	1240.2	1045	789.6	544.5
10 - 11	939.2	1115	1302.6	1465.4	1597.5	1683.4	1663.7	1541.4	1352.4	1111	919.9	831.2
11 - 12	948.0	1138	1348.1	1525.7	1651.3	1727.6	1710.1	1602.6	1388.3	1144	936.9	835.2
12 - 13	923.9	1142	1376.8	1532.7	1670.3	1740.2	1725.0	1618.2	1408.8	1171	938.4	825.1
13 - 14	915.1	1145	1380.0	1514.9	1660.7	1739.5	1720.2	1620.4	1406.8	1174	940.5	821.2
14 - 15	936.2	1150	1328.1	1484.0	1626.8	1725.1	1725.8	1614.3	1375.6	1165	942.4	841.4
15 - 16	929.0	1136	1293.9	1435.8	1551.8	1677.7	1686.9	1566.0	1314.7	1098	913.1	841.1
16 - 17	751.1	1060	1202.9	1303.6	1405.8	1550.9	1568.7	1438.0	1179.1	915.9	547.8	472.0
17 - 18	129.3	493.7	879.0	1052.7	1173.6	1322.1	1350.8	1204.2	803.8	261.5	25.0	17.8
18 - 19	0.0	4.4	159.2	440.9	715.5	910.8	930.9	619.2	128.4	1.1	0.0	0.0
19 - 20	0.0	0.0	0.0	9.9	105.5	268.6	227.7	44.0	0.0	0.0	0.0	0.0
20 - 21	0.0	0.0	0.0	0.0	0.0	3.1	0.8	0.0	0.0	0.0	0.0	0.0
21 - 22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22 - 23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23 - 24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sum	7088	9441	12133	14643	16806	18299	17950	15894	12753	9756	7159	6085

C. Electrolyzer electricity consumption in each suitable site

Table 21. Electrolyzer electricity input Mijares - Castellón de la Plana (kWh)

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1 - 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2 - 3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3 - 4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4 - 5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5 - 6	0.0	0.0	0.0	0.0	1.3	5.5	0.7	0.0	0.0	0.0	0.0	0.0
6 - 7	0.0	0.0	0.0	21.4	188.9	284.9	179.6	43.3	2.4	0.0	0.0	0.0
7 - 8	0.0	0.0	67.7	468.3	784.8	885.8	772.8	519.8	259.0	59.5	0.6	0.0
8 - 9	27.9	172.2	647.1	1030.0	1030.0	1030.0	1030.0	1030.0	879.5	587.0	215.3	42.8
9 - 10	499.1	833.9	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	769.7	498.8
10 - 11	893.1	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	891.3	807.0
11 - 12	900.7	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	887.2	792.4
12 - 13	868.6	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	879.6	765.0
13 - 14	856.6	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	892.0	768.8
14 - 15	890.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	902.0	802.6
15 - 16	904.4	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	880.8	796.7
16 - 17	674.5	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	839.9	474.2	396.8
17 - 18	80.1	421.0	859.2	1030.0	1030.0	1030.0	1030.0	1030.0	721.3	216.2	15.8	10.4
18 - 19	0.0	2.9	145.2	441.4	706.8	870.8	873.5	562.0	108.5	1.1	0.0	0.0
19 - 20	0.0	0.0	0.0	16.9	107.1	279.3	251.7	38.8	0.0	0.0	0.0	0.0
20 - 21	0.0	0.0	0.0	0.0	0.0	5.6	2.4	0.0	0.0	0.0	0.0	0.0
21 - 22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22 - 23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23 - 24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 22. Electrolyzer electricity input - Turia (kWh)

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1 - 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2 - 3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3 - 4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4 - 5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5 - 6	0.0	0.0	0.0	0.0	0.0	2.2	0.0	0.0	0.0	0.0	0.0	0.0
6 - 7	0.0	0.0	0.0	20.2	175.8	255.2	161.0	25.9	0.5	0.0	0.0	0.0
7 - 8	0.0	0.0	39.8	448.4	777.7	844.7	758.4	487.5	248.9	50.2	0.6	0.0
8 - 9	29.5	144.3	624.3	1030.0	1030.0	1030.0	1030.0	1030.0	885.9	588.1	194.9	44.2
9 - 10	515.6	845.3	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	791.8	514.9
10 - 11	917.9	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	921.4	834.1

11 - 12	929.9	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	918.6	826.4
12 - 13	900.5	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	911.9	792.9
13 - 14	891.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	923.6	794.0
14 - 15	923.7	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	947.0	833.7
15 - 16	933.9	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	925.3	839.4
16 - 17	723.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	894.1	528.0	447.3
17 - 18	91.5	472.9	893.3	1030.0	1030.0	1030.0	1030.0	1030.0	778.7	243.2	21.1	14.4
18 - 19	0.0	12.5	158.5	440.6	718.3	881.5	921.2	608.6	120.5	1.1	0.0	0.0
19 - 20	0.0	0.0	0.0	10.1	110.3	278.8	263.8	55.9	0.0	0.0	0.0	0.0
20 - 21	0.0	0.0	0.0	0.0	0.0	3.4	3.1	0.0	0.0	0.0	0.0	0.0
21 - 22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22 - 23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23 - 24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 23. Electrolyzer electricity input. Vinalopó - Alacantí (kWh)

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1 - 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2 - 3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3 - 4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4 - 5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5 - 6	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0
6 - 7	0.0	0.0	0.0	7.1	144.3	240.5	131.5	24.8	0.5	0.0	0.0	0.0
7 - 8	0.0	0.0	39.4	421.2	771.3	861.0	752.7	496.6	227.0	53.3	0.6	0.0
8 - 9	49.6	182.8	633.4	1030.0	1030.0	1030.0	1030.0	1030.0	928.0	612.1	205.1	56.1
9 - 10	566.6	870.5	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	789.6	544.5
10 - 11	939.2	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	919.9	831.2
11 - 12	948.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	936.9	835.2
12 - 13	923.9	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	938.4	825.1
13 - 14	915.1	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	940.5	821.2
14 - 15	936.2	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	942.4	841.4
15 - 16	929.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	913.1	841.1
16 - 17	751.1	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	1030.0	915.9	547.8	472.0
17 - 18	129.3	493.7	879.0	1030.0	1030.0	1030.0	1030.0	1030.0	803.8	261.5	25.0	17.8
18 - 19	0.0	4.4	159.2	440.9	715.5	910.8	930.9	619.2	128.4	1.1	0.0	0.0
19 - 20	0.0	0.0	0.0	9.9	105.5	268.6	227.7	44.0	0.0	0.0	0.0	0.0
20 - 21	0.0	0.0	0.0	0.0	0.0	3.1	0.8	0.0	0.0	0.0	0.0	0.0
21 - 22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22 - 23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23 - 24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

D. LCOH calculation in each suitable site

Table 24. LCOH calculation in location 1

Year	H_2 production (kgH_2)	Elec Capex (€)	PVCapex (€)	Elec Opex (€)	PV Opex (€)	H_2 tank (€)	Water Opex (€)	Total (€)
0	62495.6	1350000.0	1259538.6	5165.0	18666.6	736400.0	594.5	3370364.8
1	59151.4	0.0	0.0	5003.4	18082.6	0.0	562.7	23648.7
2	56814.5	0.0	0.0	4846.8	17516.8	0.0	532.6	22896.2
3	54569.9	0.0	0.0	4695.2	16968.7	0.0	504.1	22168.0
4	52414.0	0.0	0.0	4548.3	16437.8	0.0	477.1	21463.1
5	50343.2	0.0	0.0	4406.0	15923.4	0.0	451.6	20781.0
6	48354.3	0.0	0.0	4268.1	15425.2	0.0	427.4	20120.7
7	46444.0	0.0	0.0	4134.6	14942.5	0.0	404.5	19481.6
8	44609.1	0.0	0.0	4005.2	14475.0	0.0	382.9	18863.1
9	42846.7	0.0	0.0	3879.9	14022.1	0.0	362.4	18264.4
10	41153.9	0.0	0.0	3758.5	13583.3	0.0	343.0	17684.8
11	40992.2	380652.4	0.0	3640.9	13158.3	0.0	324.7	397776.2
12	39372.7	0.0	0.0	3526.9	12746.6	0.0	307.3	16580.9
13	37817.2	0.0	0.0	3416.6	12347.8	0.0	290.8	16055.2
14	36323.1	0.0	0.0	3309.7	11961.4	0.0	275.3	15546.4
15	34888.1	0.0	0.0	3206.1	11587.2	0.0	260.5	15053.8
16	33509.7	0.0	0.0	3105.8	11224.6	0.0	246.6	14577.0
17	32185.9	0.0	0.0	3008.6	10873.4	0.0	233.4	14115.4
18	30914.3	0.0	0.0	2914.5	10533.2	0.0	220.9	13668.6
19	29692.9	0.0	0.0	2823.3	10203.6	0.0	209.1	13236.0
20	28519.8	0.0	0.0	2735.0	9884.3	0.0	197.9	12817.2
Total	903412.4	1730652.4	1259538.6	80398.3	290564.5	736400.0	7609.3	4105163.2
LCOH (€/kgH_2)		**1.92**	**1.39**	**0.09**	**0.32**	**0.82**	**0.01**	**4.54**

Table 25. LCOH calculation in location 2

Year	H_2 production (kgH_2)	Elec Capex (€)	PV Capex (€)	Elec Opex (€)	PV Opex (€)	H_2 tank (€)	Piping (€)	Water Opex (€)	Total (€)
0	62935.9	1350000.0	1259538.6	5165.0	18666.6	736400.0	85466.0	2253.8	3457490.0
1	59568.1	0.0	0.0	5003.4	18082.6	0.0	0.0	2133.2	25219.1
2	57214.7	0.0	0.0	4846.8	17516.8	0.0	0.0	2019.0	24382.6
3	54954.3	0.0	0.0	4695.2	16968.7	0.0	0.0	1911.0	23574.9
4	52783.2	0.0	0.0	4548.3	16437.8	0.0	0.0	1808.7	22794.7
5	50697.9	0.0	0.0	4406.0	15923.4	0.0	0.0	1711.9	22041.3
6	48694.9	0.0	0.0	4268.1	15425.2	0.0	0.0	1620.3	21313.6
7	46771.1	0.0	0.0	4134.6	14942.5	0.0	0.0	1533.6	20610.7
8	44923.3	0.0	0.0	4005.2	14475.0	0.0	0.0	1451.5	19931.7
9	43148.5	0.0	0.0	3879.9	14022.1	0.0	0.0	1373.9	19275.8
10	41443.8	0.0	0.0	3758.5	13583.3	0.0	0.0	1300.4	18642.2
11	41280.9	380652.4	0.0	3640.9	13158.3	0.0	0.0	1230.8	398682.4

12	39650.0	0.0	0.0	3526.9	12746.6	0.0	0.0	1164.9	17438.5
13	38083.6	0.0	0.0	3416.6	12347.8	0.0	0.0	1102.6	16867.0
14	36579.0	0.0	0.0	3309.7	11961.4	0.0	0.0	1043.6	16314.7
15	35133.8	0.0	0.0	3206.1	11587.2	0.0	0.0	987.7	15781.0
16	33745.8	0.0	0.0	3105.8	11224.6	0.0	0.0	934.9	15265.3
17	32412.6	0.0	0.0	3008.6	10873.4	0.0	0.0	884.8	14766.9
18	31132.0	0.0	0.0	2914.5	10533.2	0.0	0.0	837.5	14285.2
19	29902.1	0.0	0.0	2823.3	10203.6	0.0	0.0	792.7	13819.6
20	28720.7	0.0	0.0	2735.0	9884.3	0.0	0.0	750.3	13369.6
Total	909776.2	1730652.4	1259538.6	80398.3	290564.5	736400.0	85466.0	28847.0	4211866.9
LCOH (€/kgH_2)		**1.90**	**1.38**	**0.09**	**0.32**	**0.81**	**0.09**	**0.03**	**4.63**

Table 26. LCOH calculation in location 3

Year	H_2 production (kgH_2)	Elec Capex (€)	PV Capex (€)	Elec Opex (€)	PV Opex (€)	H_2 tank (€)	Water Opex (€)	Total (€)
0	63252.44	1350000.00	1259538.64	5165.00	18666.64	736400.00	2103.15	3371873.43
1	59867.70	0.00	0.00	5003.39	18082.57	0.00	1990.61	25076.57
2	57502.48	0.00	0.00	4846.84	17516.78	0.00	1884.09	24247.71
3	55230.71	0.00	0.00	4695.18	16968.69	0.00	1783.27	23447.14
4	53048.68	0.00	0.00	4548.27	16437.75	0.00	1687.84	22673.87
5	50952.87	0.00	0.00	4405.96	15923.43	0.00	1597.52	21926.91
6	48939.85	0.00	0.00	4268.10	15425.19	0.00	1512.04	21205.33
7	47006.37	0.00	0.00	4134.56	14942.55	0.00	1431.12	20508.23
8	45149.27	0.00	0.00	4005.19	14475.01	0.00	1354.54	19834.74
9	43365.54	0.00	0.00	3879.87	14022.09	0.00	1282.06	19184.02
10	41652.28	0.00	0.00	3758.47	13583.35	0.00	1213.45	18555.27
11	41488.57	380652.39	0.00	3640.87	13158.34	0.00	1148.52	398600.11
12	39849.46	0.00	0.00	3526.95	12746.62	0.00	1087.06	17360.63
13	38275.11	0.00	0.00	3416.59	12347.79	0.00	1028.89	16793.27
14	36762.96	0.00	0.00	3309.69	11961.43	0.00	973.83	16244.96
15	35310.55	0.00	0.00	3206.13	11587.17	0.00	921.72	15715.02
16	33915.52	0.00	0.00	3105.81	11224.61	0.00	872.40	15202.83
17	32575.61	0.00	0.00	3008.64	10873.40	0.00	825.72	14707.75
18	31288.63	0.00	0.00	2914.50	10533.18	0.00	781.53	14229.21
19	30052.50	0.00	0.00	2823.30	10203.60	0.00	739.71	13766.62
20	28865.20	0.00	0.00	2734.97	9884.34	0.00	700.13	13319.43
Total	914352.28	1730652.39	1259538.64	80398.28	290564.52	736400.00	26919.21	4124473.03
LCOH (€/kgH_2)		**1.89**	**1.38**	**0.09**	**0.32**	**0.81**	**0.03**	**4.51**